PETROGRAPHY, FABRIC ANALYSIS AND ORIGIN OF THE TALCHIR BOULDER BED IN THE DAMODAR VALLEY COALFIELDS

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A B S T R A C T

This work, based on recent techniques of examination of sediments, includes a detailed petrographic and fabric study of the Talchir boulder bed in the Damodar Valley Coalfields. The observations of previous workers were purely qualitative and based on indirect evidences and criteria of doubtful nature. The quantitative data given by the author is original and has been interpreted in the light of the results available on work of a similar nature done in other countries.

As a result of this investigation it is established that the Talch boulder bed in the Damodar Valley Coalfields is of ultimate glacial origin it is shown that two glacial advances took place during the early Talchir times. The basal boulder bed is a true tillite, but the upper boulder b has been reworked and turned over by glacial streams so that the debris resembles an outwash deposit. The directions of ice movement during th deposition of the two boulder beds have been established and an attempt been made to reconstruct the sedimentological conditions prevailing ove area during the early Talchir times.

Pebble counts made in the field indicate that the coarse fraction of the boulder bed exhibits a complex and varied lithology and that the bulk of the debris is of local origin. No systematic regional variation in lithology is noticeable. Roundness of pebbles and cobbles was determined using Krumbein's visual estimation method. The values of mean roundness in the basal boulder bed are comparable to those of the pebbles and cobbles in true glacial deposits. The pebbles and cobbles of the upper boulder bed and the cross-bedded horizons which resemble the glacial outwash deposits show higher values of mean roundness.

About 5-10% of the pebbles and cobbles of the basal bed are flat-iron shaped, while only 1-3% in the upper bed are of this shape. There does not exist any significant regional variation in the mean sphericity values of the large particles in the different horizons. The striation pattern on facetted pebbles and cobbles is parallel to their long axes; the coarse particles of the cross-bedded horizons are rounded and bear no striations.

Eighty samples of the fine fraction have been fully analysed by sieving and by the pipette method and the results have been presented in histograms, cumulative curves and in a triangular compositional diagram. The data has also been treated statistically. As a result it has been found that the basal bed has the textural composition of a tillite, while the upper bed and the cross-bedded horizons resemble glacial outwash deposits. This conclusion is corroborated by a petrological study of the fine fraction. The heavy mineral suits of the two boulder beds are similar. It is, therefore, inferred that the provenance of the two beds is the same.

The orientation of 3000 long axes of pebbles and cobbles has been measured. The data is presented in semi-circular histograms and in contoured fabric diagrams. The orientation data has also been statistically treated and the mean direction of preferred orientation has been determined. The fabric of the basal boulder bed resembles that of tills and indicates a NW-SE direction of ice movement. The fabric of the upper boulder bed is essentially similar to that of fluvial gravels and shows that the sediment was transported from the west to east. The cross-bedded horizons show variable fabric patterns, but the mean direction of preferred orientation is the same as that in the upper bed.

In the light of these facts it is concluded that the basal boulder bed is a true tillite and was deposited by an ice sheet which had moved in from the north-west. The shales and sandstones separating the two boulder beds were deposited in glacial lakes after the ice sheet had receded. A second ice sheet then moved into the area from the west and deposited the upper boulder bed which was subsequently reworked by the glacial streams. The cross-bedded horizons represent the completely washed and reworked portions of the upper boulder bed.

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INTRODUCTION

The Gondwana system has a unique position in the stratigraphy of India. Not only does its lithology and mode of formation stand in marked contrast to other formations, it also yields over 98% of the annual production of coal in the country. It is not surprising, therefore, that the Gondwanas, specially the coal-bearing strata, should have received much attention of eminent geologists.

Several valuable contributions were made by earlier workers towards elucidating the conditions of deposition of the Gondwana sediments (Blanford & others 1856; Hughes, 1867; Ball, 1867; Oldham, 1893; Simpson and Ball, 1922; Jowett, 1925; Fox, 1930, 1934; Gee, 1932). These studies were qualitative and based essentially on indirect evidences for the reason that most of the modern techniques of study of sediments were not available to the earlier workers.

Studies on modern lines towards a clearer understanding of the Gondwana sediments commenced about the year 1936. These studies consisted of heavy mineral determination of a few formations of the coal measures (Roy and Sharma, 1936), and petrographic investigation including shape and size analyses of some sandstones (Roy, 1940; Sen and Ray Chowdhury, 1948; Sen, 1949). Recently important contributions have been made to our knowledge of the palaeocurrent system during the Gondwana period (Jacob, 1952; Jacob & others, 1959; Ganju & Srivastava, 1959; Ganguli, 1960). Some valuable information is also available during the Gondwana period in the different parts of the country (Rao, 1957; Jacob & others, 1959). It is important to note, however, that these studies were mainly local in character and did not attempt to give a unified picture of the Gondwana sedimentation.

It is obvious that no single contribution can possibly solve all the problems pertaining to the Gondwana sedimentation. Nevertheless an attempt has to be made to systematise the study and to extend it on a regional basis so that conclusions of some significance may emerge. Krishnan (1958, p. 433) very rightly stresses that "detailed studies should now be undertaken for determining the sources of sediments and the directions of drainage as they will help us understand the stratigraphical and structural features". The present study is an attempt in the same direction.

Although the entire Gondwana system offers excellent opportunities for detailed sedimentological studies, the Talchir boulder bed was selected for the purpose of this investigation for the following reasons:-

1. It constitutes the bottom-most bed of the Gondwana system in all the coalfields of Peninsular India and, therefore, contains a possible clue to the physical, climatic and geological conditions prevailing at the beginning of a great cycle of sedimentation.

2. The Talchir boulder bed has been used as an "index" horizon in the stratigraphy of India and has thus been widely used for correlation purposes.

3. A systematic study of this horizon has been neglected so far

although it constitutes one of the most interesting units of the Gondwana system.

4. For any systematic study of the Gondwanas, it is necessary to deal with the different formations separately. The oldest unit would be the most suitable choice.

In order to keep the problem within definite limits, and yet to maintain its regional character, it was decided to investigate this lowest unit of the Gondwana sequence in the Raniganj, Jharia, Bokaro, Ramgarh and North and South Karanpura coalfields. *Fox* (1934, p. 75) has grouped these coalfields together and designated them collectively as the "Damodar Valley Coalfields". The boulder bed is very well exposed in these coalfields which form an almost continuous chain from east to west for a distance of about 168 miles. Further, some of the largest and most productive coalfields of the country are included in this group.

The heterogeneous character and the very wide range of size of the particles that constitute the boulder bed render its study rather difficult. The problems of weathering and the inaccessibility of several outcrops in many coalfields creates further difficulties. But for these drawbacks this horizon provides all that is needed for an ideal sedimentological study.

The field work in connection with the present study was carried out in two stages. The various exposures of the boulder bed in the Raniganj, Jharia and Bokaro coalfields were examined in October and November 1958.

The Ramgarh and North and South Karanpura coalfields were visited in December 1958 and January 1959. During these two visits, all the important and accessible outcrops of the boulder bed were examined.

In order to facilitate the field and laboratory investigations, the coarse debris and the matrix of the boulder bed were examined separately. The dividing line between the coarse and fine fractions was chosen arbitrarily at 4 mm. size. Particles larger than this size were studied with respect to their lithology, roundness, shape, surface, textures and fabric. Lithological studies were made in the field with the help of pebble counts at each exposure while Krumbein's (1941) method was used in the field for the determination of roundness of quartzite pebbles in the boulder bed. A fabric study was also made in the field by measuring the orientation of 3000 long axes of rod-shaped particles in as many exposures of the boulder bed as was possible. The data obtained from the above studies was statistically treated.

Particles smaller than 4 mm. were considered as forming the fine fraction of the boulder bed. No field study was made on this fraction but carefully chosen samples were collected from each outcrop and studied in the laboratory with respect to their mechanical composition, micropetrology and heavy mineral content.

The methods of sampling, field measurements and techniques used in the present study have been described in detail elsewhere.

The author has attempted to work out the probable origin of the

Talchir boulder bed. This includes the study of the provenance, the mode and direction of sediment transport and the nature of the basin of deposition. It is hoped that this study, based on modern sedimentary techniques, would substantially contribute towards a better understanding of the problems of sedimentation in the Damodar Valley region at the very beginning of the Gondwana period.

The author learnt the recent techniques and methods of the study of sediments under the able guidance of Professor F.J. Pettijohn, Professor of Geology, Johns Hopkins University, Baltimore, U.S.A., where he went as a Smith-Mundt and Fulbright grantee in 1956.

The work has been carried out in the laboratories of the Geology Department, Aligarh Muslim University, Aligarh, under the able guidance of Professor P.N. Ganju, Ph.D. (Durham), Ph.D. (Lucknow), A.M.I.Min.E., F.G.S., F.N.I.

The author is indebted to Professor Ganju for kindly suggesting the problem and offering constant guidance, encouragement and help throughout the work. He is also grateful to his one time teacher, Professor F.J. Pettijohn and to Dr. R. Teichmuller of West Germany, who have offered helpful suggestions and criticism. Sincere thanks are also due to his colleagues, Mr. S.H. Rasul, Dr. N. Ahmad, Mr. I.D. Pant, Mr. S.M. Casshyap and Mr. Athar Husain for their ready cooperation and encouragement throughout the work.

CHAPTER I

GEOLOGY OF THE DAMODAR VALLEY COALFIELDS

The name "Gondwana System" was proposed by H.B. Medlicott in 1872 (see Holland, 1926, p. 78) for a thick pile of fresh water sediments ranging in age from Upper Carboniferous to Lower Cretaceous. The rocks of this system are varied in character and lithology and consist of tillites, conglomerates, sandstones and shales with intercalated coal seams.

The mode of formation of the Gondwana sediments has been a matter controversy since long. Oldham (1893, p. 151) expressed the view that these rocks were of fluviatile origin and that the sediments were deposited in large river valleys. Fox (1931, p. 47) favours a lacustrine origin for these sediments. The rocks of the Damodar valley coalfields have been considered by him as being formed in an eastward extension of a basin extending probably from south Rewah upto the Assam Himalayas.

The structural nature of the Gondwana basins is also disputed. Blanford & others (1856) and Oldham (1893, p. 153) believed that the Gondwana coalfields occupy areas of depression produced after the deposition of the rocks. Simpson and Ball (1922, p. 2) favoured the view that these coalfields represent "basins of original deposition" at some places, while at others they are preserved due to faulting. Greisbach (1880, p. 12), Jowett (1925, p. 139), Gee (1932, p. 27; 1941, p. 4) and

Krishnan (1956, p. 303) are of the opinion that originally the Gondwana sedimentation must have extended over larger tracts. Fox (1934, p. 23), on the other hand, believes that these basins were block faulted and that the Gondwana sediments were deposited in these well defined structural basins. Wadia (1939, p. 125) also holds generally the same view but states that "some of the boundary faults may be of post-Gondwana age".

There are two important features of the Gondwana rocks in the Damodar valley region that deserve mention. The first is the sharply faulted nature of the southern boundary of all the coalfields; the faults run almost parallel to one another in all cases and are, in turn, co-incident with the foliation of the basement Archaean rocks. The throw of these faults is considerable and has been estimated by Gee (1932, 1941) to be of the order of 9000' and 5000' in the Raniganj and Jharia coalfields respectively. In some coalfields, as in that of Bokaro, the northern boundary is also faulted, but this fault is never as prominent as the southern one. Gee (1941, p. 4) thinks that the faulting took place during the Mesozoic times.

The second interesting feature of the coalfields is the occurrence of numerous ultrabasic dykes and sills which have invaded the entire sequence of the sediments. Gee (1941, p. 6) considers these to be closely associated with faulting of the Gondwanas during the Mesozoic times. A second type of intrusion in the form of dykes and sills of doleritic and basaltic composition also occurs in the coalfields. Gee (loc. cit.) considers that the dykes and sills of dolerite and basalt are younger than the ultrabasic intrusions and states that the former "probably represent the intrusive phase connected with the Deccan trap vulcanicity of the Peninsula".

An outline of the geology of these coalfields based on the works of Hughes (1867), Ball (1867), Simpson and Ball (1922), Jowett (1925), Fox (1930, 1934) and Gee (1932), is given below. A geological map of the coalfields is reproduced in Fig. 1.

RANIGANJ COALFIELD

This coalfield is located about 130 miles north-west of Calcutta between the east longitudes of 87°36' and 87°20 on the extreme eastern end of the Damodar Valley Coalfields. The Gondwana rocks cover an area of about 600 sq. miles.

According to Gee (1932, p. 21), the general stratigraphic sequence in this coalfield is as follows:-

Recent and Sub-recent	Aluvium and laterite		
Upper Gondwana	Supra Panchets		1000 Feet
Lower Gondwana	Panchet Series		2000 "
	Damada Series	Raniganj measures	3400 "
		Ironstone shales	1200 "
		Barakar measures	2100 "
	Talchir Series		900 "

The Talchirs are exposed mainly towards the northern boundary of the basin. Gee (loc. cit. p. 23) has reported the occurrence of small patches of Talchir rocks along the southern boundary also but these exposures are small and insignificant. The bulk of the Talchir series consists of green argillaceous sandstones and olive green splintery shales. The boulder bed at the base of this series is exposed in the northeast corner of the basin. These outcrops are generally small and of no great thickness.

The Barakar measures constitute the lowest subdivision of the Damuda series and consist of an alternating sequence of sandstones, shales and coal seams. The ironstone shales consist essentially of clay ironstones and black carbonaceous shales. No coal has been reported from this horizon. The rocks of the Raniganj measures do not differ much from those of the Barakars in their lithology.

The rocks of the Panchet series rest over the Raniganj measures in the central, eastern and southern parts of the coalfield. The lower part of this series consists of green shales and greenish brown sandstones; the upper part is comprised of a thick sequence of sandstones and red shales with intercalated white clays.

The only upper Gondwana rocks in this field are the Supra Panchets which occur along its southern boundary, capping several hill tops. This series consists of coarse pebbly sandstones with bands of red clay.

Dolerite dykes and sills of mica-peridotite are numerous in the field and have resulted in a large scale destruction of the coal seams.

The Gondwana sediments in the eastern part of the field are covered with laterite and lateritic gravels. These have been considered Recent and Sub-recent in age.

The southern boundary of the field is sharply faulted against the Archaeans and the throw of this fault has been estimated by Gee (1932, 1941) to be of the order of over 9000 feet. The dips of the sedimentaries show a southerly inclination.

Mehta (1956) has resurveyed the field recently but his work concerns mainly the mapping and correlation of coal seams.

JHARIA COALFIELD

The Jharia coalfield covers an area of about 175 sq. miles and lies between 86°06' and 86°30' east longitudes. Its easternboundary is only about 16 miles from the western limit of the Raniganj coalfield, while it is separated from the Bokaro coalfield on the west by a two mile strip of Archaean rocks.

The stratigraphic sequence as given by Fox (1930), is as follows:-

Lower Gondwana	Damudas	Raniganj series	1840 Feet
		Barren measures	2080 "
		Barakar series	2000 "
	Talchir series		800 "

The area occupied by the Talchir rocks is small as compared to the total area of the Gondwana sediments. Their lithology is generally the same as seen in the Raniganj coalfield. The boulder bed at the base of the series as estimated by Fox (1930, p. 25), is about 50 feet thick.

The rocks of the Damuda series are very similar in lithology to their counterparts in the Raniganj coalfield. The middle division of this series has been termed "Barren Measures" by Fox (loc. cit.) in preference to "Ironstone Shales" of the Raniganj coalfield because true ironstones are rare in this field. However, Mehta and Murthy (1957, p. 7) have suggested the use of the term "Middle Measures" for this division in view of the fact that it is not entirely barren as thin coal seams occur occasionally. The sandstones of the Raniganj and Barakar groups are very similar in lithology, texture and composition and are often indistinguishable in the hand specimen. Roy and Sharma (1936) have, however, shown that very significant differences exist in their heavy mineral contents.

More recently Jacob and others (1959) have made a sedimentological study in parts of Jharia and East Bokaro coalfields and have classified the Gonwana rocks of these areas on the basis of facies. They have also determined the petrographic characteristics of the individual facies.

No stratified rocks younger than the Raniganj series are found within the limits of this coalfield.

Igneous intrusions of the same nature as found in the Raniganj coalfield occur abundantly in this basin also. Peridotite dykes and sills, according to Fox (loc. cit., p. 113), occur closely associated with coal seams and faults. Dolerite dykes, on the other hand, cut accross the strata and are apparently unconnected with structural features.

The southern boundary of the field is sharply faulted bringing the rocks of the Raniganj series in juxtaposition with the Archaeans. The throw of this fault has been estimated by Fox (loc. cit., p. 147) to be about 5000 feet. The northern boundary of the field is also criss-crossed by numerous smaller faults. Fox (loc. cit., p. 153) also mentions the occurrence of "several anticlinal or dome-like features and of corresponding synclinal or trough-like irregularities in the main structural basin of the Jharia coalfield".

BOKARO COALFIELD

The Gondwana rocks in this coalfield occupy an area of about 220 sq. miles. The coalfield stretches from east to west for about 40 miles and its average width from north to south is about 6½ miles. It is separated from the Jharia coalfield in the east by a two-mile strip of the Archaeans and from the North Karampura coalfield on the western side by a narrow stretch of about one mile.

According to Hughes (1867), the succession of the Gondwana strata in this field, is as follows:-

Panchet Series	Upper Lower
Damuda Series	Raniganj Group Ironstone shale Group Barakar Group
Talchir Series	

The area occupied by the Talchir rocks is very small as compared to the total area of the Gondwana sediments in this field. The rocks of this series occur mainly on the western and eastern ends of the field, though numerous small outliers of these rocks are also found along the northern boundary. Hughes (loc. cit., p. 6) assigns a thickness of 500 feet to this series in the Mando-Indrajabar section. The exposures of the boulder bed at the base of this series are very poor in the eastern part of the field, while those on the western side, though small in aerial extent, are good.

The Damuda serie lies unconformably over the underlying rocks. There appears no unconformity between the lower and the middle subdivisions of the Damudas, but the Raniganj group of rocks lies slightly unconformably over the Ironstone shales.

The Panchet series is also unconformable to the underlying rocks.

According to Hughes (loc. cit., p. 69) the upper part of this series may be correlated with the Mahadevas.

Both the northern and southern boundaries of this coalfield are faulted against the Archaeans, the northern fault being more prominent. Fox (1934, p. 120) is of the opinion that "the coalfield has been preserved by the trough faulting". Dykes of dolerite and mica peridotite are common and have adversely affected the coal seams. Recently Casshyap (1960) has noted the occurrence of some clastic dykes in the Barakar rocks of East Bokaro.

RAMGARH COALFIELD

The Ramgarh coalfield which lies between 85°30' and 85°45' east longitudes, is the smallest among the Damodar Valley Coalfields and occupies an area of only 40 sq. miles. It has been named after the town of Ramgarh which is located at the extreme western end of the coalfield.

The succession of the Gondwana rocks in this field, as given by Ball (1867), is as follows:-

Damuda Series	Raniganj Group	?	
	Ironstone shale Group	1200	Feet
	Barakar Group	3000 ?	"
Talchir Series		850-900	"

The best exposures of the Talchir rocks occur at the northern tip of the field as well as along its eastern boundary. A few isolated patches of these rocks also occur along the northern and southern boundaries of the coalfield. Exposures of the boulder bed are excellent in the northern occurrences but elsewhere they are poor. The general characters of these rocks are essentially the same as observed in the other coalfields.

The Barakar rocks overlap the Talchirs over a major part of the coalfield and occupy as much as 80% of the total area covered by all the Gondwana formations. The exposures of the Ironstone shales and Raniganj group of rocks are very small and these occur at the western end of the coalfield.

In common with the other coalfields of the Damodar Valley, the southern boundary of this field also is sharply faulted against the Archaeans. The sedimentaries have also been invaded by dykes and sills of dolerite and mica peridotite.

KARANPURA COALFIELDS

The Karanpura coalfields, lying at the extreme western end of the Damodar Valley Coalfields, are two separate basins of Gondwana rocks connected with each other by a narrow patch of Talchir rocks. The larger of the two lies to the north and is called the North Karanpura coalfield, while the smaller one, situated at the south-eastern corner of the former, is referred to as the South Karanpura coalfield. The combined area of the two coalfields is about 550 sq. miles, that of the smaller one alone being only 75 sq. miles.

According to Jowett (1925), the following sequence of the Gondwana rocks occurs in these fields:-

Upper Gondwana	Mahadeva Series		
Lower Gondwana	Panchet Series		
	Damuda Series	Raniganj stage	
		Ironstone shale stage	
		Barakar stage	
	Talchir Series	Karharbari stage	(?)
		Talchir stage	

The Talchir rocks are best exposed in the areas around Misroul and Raie in the north-western and southern portions of the North Karanpura coalfield respectively. Numerous small patches of these rocks also occur at various places along the northern and eastern boundary of the field. In South Karanpura, the Talchir exposures are generally poor and insignificant. The outcrops of the boulder bed in the northern field are excellent, but in the southern field the boulder bed is poorly exposed.

The rocks of the Damuda series are very well developed in both the coalfields and cover the greatest area. Fox (1934, p. 137) prefers the term "Barren Measures" for the middle division of the Damudas for the reason that true Ironstones are by no means characteristic of this group of rocks.

The Panchet series lies unconformably over the Raniganj group and is developed at the base of the prominent hills in the North Karanpura coalfield. This series is overlain by the Mahadevas, which have been considered as equivalents of the Supra Panchets of the Raniganj coalfield. The presence of an unconformity between the Panchets and the Mahadevas has been noted by Jowett (loc. cit., p. 137). No Panchet and Mahadeva rocks have been reported from the South Karanpura coalfield.

The southern boundary of these coalfields is sharply faulted and numerous, small oblique faults occur all along the boundary, but the throw of the individual faults is not great. Igneous intrusions of the kind seen in other coalfields also occur in this area, but these are not so abundant.

CHAPTER II

THE TALCHIR BOULDER BED

The name "Talchir Series" was given by W.T., and H.F. Blanford and W. Theobald (1856) after the state of Talchir where the rocks were first described.

The Talchir series in all the coalfields under discussion has characteristic features and can be readily distinguished from the other Gondwana formations. This series is the oldest in the Gondwana sequence and lies directly over the Archaeans, the junction between the two being either sharply faulted or distinctly unconformable.

The most characteristic unit of this series is a boulder bed at or near its base but its thickness is very insignificant as compared to the total thickness of the series. In a general way its thickness decreases as it is traced from west to east through the various coalfields of the Damodar Valley. This characteristic was noted by Gee (1932, p. 37), who stated that "compared with the western tracts, the boulder bed in Raniganj is of no great thickness". But the importance of the boulder bed does not lie in its thickness; its peculiar character and variable composition and texture make its study interesting.

The boulder bed, as a rule, occurs at the base of the Talchir series, but several instances have been noted by Ball (1867, p. 6), Fedden (1875, p. 17) and Jowett (1925, p. 18) where shales and sandstones of the Talchir series have been found resting directly against the Archaeans. Detailed field work by the present author in the Damodar Valley Coalfields has revealed that whenever the boulder bed is absent from the base at a given locality, the junction between the Talchirs and the Archaeans is a faulted one. Further, two horizons of the boulder bed separated from each other by varying thicknesses of shales and sandstones, occur in a given sequence provided the rocks have not been subjected to faulting. The two horizons of the boulder bed, referred to as the "basal" and "upper" in the following pages, can be distinguished from each other by their colour, mechanical composition and mineralogy of the matrix. Important differences between the two also exist in the sphericity, roundness, surface textures and fabric of the coarser particles constituting them.

The constituents of the boulder bed are not generally stratified. While referring to similar rocks in the North Karanpura coalfield, Jowett (1925, p. 11) stated that the rocks are "exceedingly variable and irregular in character, with no definite stratification". Greisbach (1880, p. 14) had noted this characteristic earlier in the Ramkola & Tatapani coalfields. Blanford (1872, p. 57), Fedden (1875, p. 17) and Fox (1934, p. 12) have observed faint bedding in the boulder bed of the Talchir series. Field investigations by the author show that, as a general rule, the basal boulder bed is devoid of stratification and is more or less a jumbled up mass of boulders, cobbles and pebbles lying in an abundant, green graywacke-like matrix. This feature is clearly seen in plate 1, figs. 1 and 2. The upper boulder bed often shows crude stratification and contains lenticular pockets of sand and gravel which are rarely cross-bedded. A general view of this horizon is illustrated in plate 2, figs. 1 & 2. Thus the two divergent observations of the earlier investigators can be reconciled if one bears in mind that two horizons and not one only exist. It is very probable, as will be seen later, that the various horizons of the boulder bed have originated in different ways and that different agencies were responsible for their formation. In the light of this hypothesis, many of the structural, textural and mineralogical inconsistancies noted by the earlier workers may be adequately explained. It is of utmost importance that in dealing with the physical attributes of the boulder bed, the horizon in question is specified.

The coarse fraction of the boulder bed in the Damodar Valley region is of a complex character. The most prominent constituents are fragments of quartzites, gneisses, schists, greenstones, aplites and granites. Less common, but genetically significant ones, are pebbles and cobbles of jaspar conglomerate, chert, sandstones and fragments of shales. A few pebbles of vein quartz and practically undecomposed potash felspar also occur occasionally. These particles of all grades lie in a fine greenish or brownish to buff detrital matrix consisting of varying proportions of sand, silt and clay. It is important to note that the basal and upper horizons of the boulder bed differ considerably from each other with respect to their lithology and the nature and amount of the matrix.

There does not appear a complete agreement between the earlier workers regarding the mode of origin of the Talchir boulder bed. Blanford and others (1856) considered the agency of ground ice as the "only adequate means" by which the boulder bed in the type area could have been formed. Hughes (1867, p. 8) expressed a totally divergent view and stated that the Talchirs of the Bokaro coalfield are of marine origin. Ball (1867, p. 8) considered the Talchir rocks of the Ramgarh coalfield as shore deposits, the boulder conglomerate representing the "talus resting on the flanks of metamorphic hills". Fedden (1875, p. 17) gave several new evidences in favour of the "ground ice" theory and strongly supported the view expressed earlier by Blanford and others. Blanford (1887, p. 49) suggested that the Talchir boulders were "derived from rapid streams" which were later on floated to the basin of deposition by winter ice. Oldham (1893, p. 160) reviewed critically the earlier views on the origin of the boulder bed and concluded that its formation was probably "due to the action of a true glacier". Fermor (1914, p. 167), Simpson & Ball (1922, p. 2) and Jowett (1925, p. 4) also supported a glacial origin for these deposits. Fox (1930, p. 23; 1934, p. 103) was of the view that the boulder bed in the Jharia coalfield represented "resorted moraine material" and that a truly glacial origin was very doubtful. Gee (1932, p. 37; 1945, p. 30) considered the early Talchir conglomerates of glacial and fluvioglacial origin. Holland (1933, p. 66) did not consider all the occurrences of the boulder bed in Peninsular India as "true tillites". He suggested that the agency of floating ice was far more likely to produce these deposits. Wadia (1939, p. 129) supported a fluvio-glacial origin for these rocks. Jacob (1952, p. 163) supported a true glacial origin for most of the occurrences, but suggested that those of the type area may be of fluvio-glacial origin. Krishnan (1958, p. 415) stated that "the basal beds of the Talchir series are glacial tillites".

The geological age of the boulder bed has been critically reviewed by Holland (1933, pp. 66-86) and he assigns an Upper Carboniferous age to it. He has further shown that the Talchir boulder bed corresponds to No. 3 of the five main glacial horizons recorded in Australia.

The direction of sediment transport during the early Talchir times is a point on which opinions differ. Ball (1873, p. 28 footnote) was of the opinion that in the Bisrampur coalfield a considerable part of the debris "must have been transported .... from the neighbourhood of Sone", thus implying a southward movement of ice which was responsible for the deposition of the boulder bed. His conclusions were based entirely on lithological similarities, between "a considerable proportion of the boulders" and Vindhyan quartzite of the Sone valley. Fermor (1914, p. 167) noted the presence of some varieties of quartzites and occasional pebbles of red jaspar breccia in the Talchir boulder bed in Korea State and concluded that these have probably come from the Vindhyan and Bijawar formations respectively. These formations are exposed towards the north of the area and, therefore, the ice which transported the debris must have moved southward. Gee (1932, p. 37) is of the opinion that during the early Talchir times highlands existed to the west and northwest of the Damodar Valley Coalfields and that ice moved east and southeastwards. Fox (1930, p. 23) suggested an eastward movement of "ice sheets of an earlier age" on purely lithological grounds. Jacob (1952,

p. 163) while discussing the probable direction of ice movement during the Talchir times, suggests that "expansional flows" extended eastwards into the "Bengal-Bihar coalfield region". He, however, did not cite any evidence in support of his contentions. Subsequent studies by Jacob and others (1959) also support the same view.

The above studies are all qualitative and mainly based on lithological evidences. Ganju and Srivastava (1959) appear to be the first to have given concrete evidence regarding the direction of sediment transport during early Talchir times on the basis of fabric studies in the Jharia coalfield. Although the above study is of a preliminary character, it pretty well establishes that the regional slope during this period was towards the east and south east.

CHAPTER III

PETROGRAPHY OF THE COARSE FRACTION

The material constituting the boulder bed exhibits a large range of particle size. Pebbles, cobbles and boulders of various size lie in a fine sandy, silty or clayey matrix, which makes the study of the deposit rather difficult. In order to facilitate the study, particles larger than 4 mm. are considered as forming the 'coarse fraction' of the deposit and have been studied separately. Particles smaller than this size are regarded as forming the 'fine fraction' of the boulder bed.

The constituents of the coarse fraction have been studied with respect to their lithology, roundness, shape and sphericity and surface textures. It was felt that a study of these fundamental physical attributes would go a long way in deciphering the geological history of the deposit as a whole, as these properties reflect the geological conditions existing at the time of the formation of the rock. Further, as no studies on these lines have been made till now, it is hoped tnat [redacted] the present work may prove of some interest.

L I T H O L O G Y

The complex and varied lithology of the coarse fraction of the boulder bed was noted earlier by many investigators (Blanford and others, 1856; Ball, 1873, p. 28; Fermor, 1914, p. 167; Krishnan, 1958, p. 416). However, references to this feature were casual and qualitative and no attempt was made to study this characteristic in a more precise and quantitative manner.

In asmuch as the lithology of the coarse fraction reflects the provenance and to a limited extent the transportation history of the deposit, it is important that a quantitative study of the lithological variations be made if a thorough understanding of the deposit is desired. With this view in mind, the author made pebble counts at almost all the exposures of the boulder bed in order to get an idea of the relative abundance of the various rock types present.

Granular variation

The effect of particle size on lithology may be termed as 'granular variation'. That the lithological composition of the same sediment may change in different grade sizes was noted long ago. Such variations in large grade sizes have been studied or inferred by many workers (Trowbridge and Shepard, 1932; Krumbein, 1942; Kay and Graham, 1943; Plumly, 1948; Rubey, 1952; Holmes, 1952; Jarnefors, 1952; Dreimanis and Reavely, 1953; Potter, 1955; Davis, 1958) and by the U.S. Bureau of Reclamation (1950). It is important to note, however, that the studies of Jarnefors, Dreimanis and Reavely and Davis show that the lithology of large fragments in tills exhibit only slight variation in different grades.

Choice of grade sizes

The choice of size range for pebble count studies naturally depends on the purpose of the study and on the nature of the deposit. Davis (loc. cit. p. 92) observes: "If counts are to be made for correlation purposes, the use of a single grade size or index grade size is satisfactory. If the primary purpose is to search for indicator stones and lithologic percentages are of minor importance, then a field count using a wide range of sizes may be superior to the use of an index grade size".

Since the purpose of making pebble counts in the present investigation was both for the "search for indicator stones" as well as for comparison of the lithologies of the two horizons of the boulder bed, particles between ½ inch and 8 inches only were selected. Such a restriction of particle size was not only convenient but also necessary for the two aims had to be reconciled.

Field Procedure

One hundred to two hundred pounds of the fresh material was dug out from each outcrop and one hundred pebbles and cobbles between ½ inch and 8 inches were randomly separated by hand picking. This operation, though slow, was easily performed as the matrix of the boulder bed in most localities is rather loosely compacted; but in areas where the matrix is hard and compact, one hundred particles within the selected range were carefully chiselled out. In both cases the samples were washed, cleaned and dried. Lithologic identifications were made in the field but in doubtful cases laboratory studies were made.

The samples from the basal and the upper boulder bed (including its cross-bedded horizons) were studied separately and the data obtained at each locality was recorded.

Results

Pebble counts made at different exposures of the same horizon in any given coalfield were averaged and the composite data appears in Table 1. The data clearly shows that the metamorphic rocks constitute the most abundant lithologic type in both the horizons of the boulder bed in all the coalfields. Among the metamorphic rocks, quartzite is the most dominant type followed by gneiss, greenstone and schist of several varieties. Igneous rocks of both acid and basic varieties form the next important group but the sedimentaries are represented poorly.

There does not appear any systematic regional variation in lithologic types. The metamorphic and igneous rock fragments resemble closely the Archaean rocks and their associated intrusives which occur all around the coalfields. It is very possible that the pebbles, cobbles and boulders of metamorphic and igneous rocks have been derived from the neighbouring areas and are, therefore, of local origin. However, the sedimentary pebbles and cobbles are of genetic importance as they are identical with the conglomerates, sandstones and shales of the Vindhyan and Bijawar age.

TABLE 1: LITHOLOGICAL COMPOSITION OF THE COARSE FRACTION OF THE BOULDER BED (PER CENT)

COALFIELD	Metamorphic Rocks					Igneous Rocks		Sedimentary Rocks		
	Quartzite	Gneiss	Schist	Slate	Green-stone	Acid	Basic	Conglomerate	Sand Stone	Shale
BASAL BOULDER BED										
North Karanpura	48	20	7	1	4	12	4	1	2	1
South Karanpura	56	9	4	1	12	8	4	3	2	1
Bokaro	50	10	6	1	18	4	5	4	2	-
Ramgarh	58	4	2	-	14	6	12	2	-	2
Jharia	24	32	16	-	4	18	2	1	3	-
Raniganj	32	44	3	1	3	9	5	-	2	-
UPPER BOULDER BED										
North Karanpura	50	18	4	-	4	8	12	2	2	-
Bokaro	46	8	10	2	20	8	3	1	-	2
Ramgarh	64	2	4	-	10	4	6	-	4	6
Jharia	68	16	2	-	4	6	2	-	2	-
CROSS - BEDDED HORIZONS										
North Karanpura	46	18	3	2	13	4	8	-	4	2
Bokaro	42	16	2	-	10	22	2	-	4	2

R O U N D N E S S

The rounded nature of the pebbles and cobbles enclosed in the Talchir boulder bed was noted as long back as 1856 when Blanfords and Theobald studied these rocks for the first time in the type area. Later workers (Blanford, 1872, p. 57; 1887, p. 49; Fedden, 1875, p. 17; Oldham, 1893, p. 157; Fox, 1930, p. 25) have also pointed out this feature and many of the theories of origin of the boulder bed have been formulated with this point in view.

If roundness is an important attribute of the particles and if it has an important geological significance, its quantitative study is essential. No such study has been made on the coarse particles of the boulder bed although important conclusions have been drawn by the earlier workers on the basis of rough estimates of roundness.

It does not need explaining that roundness of clastic particles is an important attribute in tracing the transportation history of deposits. The degree of rounding of particles is a measure of the textural maturity of sediments, though its significance decreases to some extent with increasing size of the particles (Pettijohn, 1956, p. 66). Roundness studies have also been made for correlation purposes (Trowbridge and Mortimore, 1925; Hagerman, 1933) and also for determining environments of deposition (Beal and Shepard, 1956; Wascom, 1958).

Methods of measurement

Although it was known long time ago that the edges of clastic particles are modified during transport and that they get rounded with prolonged abrasion, it was Wentworth (1919, 1922 a) who, for the first time, devised a quantitative method for measurement of this property. His "roundness ratio" is defined as r1/R, where 'r1' is the radius of curvature of the sharpest edge and R the mean radius of the particle. It is to be noted, however, that Wentworth did not distinguish clearly between the shape and roundness of particles, the two different and independent variables.

Wadell (1932) clearly distinguished and defined these two fundamental attributes of clastic particles. While roundness deals with the sharpness of the edges, shape referes to their form. Roundness, as defined by Wadell, is the ratio of the average radius of curvature of the edges and corners of the grain image projected to a 'standard size' of 70 millimeters and the radius of the maximum inscribed circle. This method, though most accurate yet devised, is very slow and impracticable where many large samples are to handled.

Russel and Taylor (1937) proposed five grade terms to express the roundness of particles and the class limits for these were fixed in accordance with the Wadell method, arithmetic means being used as class mid-points. Particles were assigned to classes on the basis of comparison with photographs of standard grains. However, this method cannot be applied to larger particles unless the photographs are enlarged to the appropriate size.

Krumbein (1941) devised a much quicker method of estimation of roundness of large clastic particles by visual comparison with nine silhouettes with roundness values ranging from 0.1 to 0.9, the silhouettes having been drawn from pebbles whose roundness had already been determined by the Wadell method. The method of estimation consists of holding the pebble in such a way that its maximum surface area is visible to the observer and then comparing it with the silhouettes. The particle in then assigned a roundness value. In this way a sample of hundred pebbles can be handled in a short time with considerable accuracy.

Cailleux (1947) defined roundness as the ratio of the diameter of the sharpest corner in the plane of maximum projection and the longest axis of the particle. Van Andel and others (1954) compared the methods of Cailleux and Wadell-Krumbein and have shown that the roundness values determined by the two methods are closely related. They further concluded that the Cailleux method was more time consuming and that the data obtained by the Krumbein method "provides more detailed and more pertinent information" than that obtained by the Cailleux method.

The roundness grades proposed by Pettijohn (1949) differ from those of Russel and Taylor in two important respects. Firstly, Pettijohn adopted a geometric scale in fixing the class limits and this brings about a clearer distinction between particles having low roundness values. Secondly, particles are assigned to appropriate classes by comparison with silhouettes and not photographs, making comparisons easier and more accurate. This method is suitable only for sand sized particles and modifications are necessary if it is to be used for larger particles.

Powers (1953) defined six roundness classes and published a visual comparison chart consisting of photographs of clay models grouping particles into classes. His scale is geometric and is useful where fine distinctions are required, specially in the study of medium and fine grained clastics.

In the present study Krumbein's (1941, p. 68) roundness chart has been used for the visual estimation of roundness of pebbles and cobbles because this method was quick and large silhouettes were available for direct comparisons. Since the data had to be used primarily for determining the roundness characteristics of the two horizons of the boulder bed, a more accurate but time consuming method was not used.

Granular variation

The effect of particle size on roundness of till pebbles and fluvio-glacial gravels is not clearly known but in all probability the effects are unimportant. To overcome such effects, if they existed, particles between 2" and 8" were selected instead of chosing a particular grade size.

The composition, texture and structure of rock particles have also an important bearing on roundness; softer pebbles are more easily rounded than the harder ones. Similarly cleavable and coarse grained rock fragments tend to be more angular as compared to the fine grained and non-cleavable ones. Since the boulder bed includes a great assortment of coarse particles of varying composition, texture and structure, the roundness determinations on composite samples would not yield useful data for studying regional variations. In order to eliminate these effects, only the quartzite pebbles were taken into consideration. It is important to note that the quartzite pebbles constitute the most dominant lithologic type in both horizons of all the coalfields.

One hundred pebbles and cobbles of fine grained quartzite within the stipulated range were separated during pebble counts and roundness estimations were made on them. The data for the basal and the upper boulder bed was tabulated separately for each coalfield.

Results

The roundness statistics of each sample is summarised in Table 2, in terms of the arithmetic mean and standard deviation. The mean roundness

TABLE 2: ROUNDNESS STATISTICS OF QUARTZITE PEBBLES

COALFIELD	Basal boulder bed		Upper boulder bed		Cross-bedded horizons	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
North Karanpura	0.472	0.155	0.510	0.145	0.570	0.119
South Karanpura	0.520	0.103	.....	.....	.....	.....
Bokaro	0.536	0.113	0.558	0.078	0.598	0.088
Ramgarh	0.538	0.125	0.604	0.092	.....	.....
Jharia	0.548	0.138	0.610	0.095	.....	.....
Raniganj	0.566	0.116	.....	.....	.....	.....

of quartzite pebbles and cobbles of the basal boulder bed varies from 0.472 to 0.566 and the particles thus fall in the 'subrounded' and 'rounded' classes of Powers (loc. cit. p. 118). It is important to note that there is a progressive increase in roundness of the quartzite pebbles and cobbles from the North Karanpura to Raniganj coalfields.

The quartzite particles of the upper boulder bed show a range in roundness values from 0.510 to 0.610 and fall in the 'rounded' class of Powers (loc. cit.). Although some of the values of roundness in the two horizons overlap, the particles of the upper boulder bed are better rounded in all the coalfields. There is a marked and regular increase in roundness of the quartzite pebbles and cobbles, from the North Karanpura to Jharia coalfields. Further, it is interesting to note that, in general, the values of standard deviation are higher in the basal boulder bed than in the upper horizon and this would mean that the roundness frequency distribution in the basal boulder bed is more dispersed as compared to the upper horizon.

Unfortunately the exposures of the cross-bedded horizons of the upper boulder bed occur only in the North Karanpura and East Bokaro coalfields. Although the data on roundness of quartzite pebbles and cobbles of this horizon is meagre, a marked increase in roundness from the North Karanpura to East Bokaro coalfields is apparent.

From the above study it can be concluded that the quartzite pebbles and cobbles in the various horizons of the boulder bed show a progressive increase in roundness from the North Karanpura to Raniganj coalfields, that is, from west to east and that they are more rounded in the upper boulder bed and its cross-bedded horizons as compared to the basal bed.

S H A P E   A N D   S P H E R I C I T Y

Shape, as distinct from roundness, is an important property of clastic particles. Although, to a large extent, the ultimate shape of pebbles and cobbles is inherited and in part controlled by structures, it may also, under the influence of certain modes of transport such as glacial, be considerably modified during dispersal. The presence of characteristic forms even in a small number of particles in a deposit may throw considerable light on its origin.

Detailed studies of shape characteristic have not so far been made on the coarse debris of the Talchir boulder bed. Reference to shape and sphericity by earlier workers were vague and terms like 'facetted' and 'spheroidal' were commonly used without clearly specifying their meaning (Fedden, 1875, p. 18; Blanford, 1887, p. 49; Holland, 1893, p. 158; Fermor, 1914, p. 168). In the present investigation an attempt has been made to make a quantitative study of the shape characteristics of the pebbles and cobbles of the boulder bed.

Statements that glacial pebbles tend to have characteristic shape have often been contradicted. Mansfield (1907, p. 553) expressed the opinion that pebbles in glacial deposits show much variation with resepct to their shape and size. Gregory (1915, p. 303) also agreed with this view and stated that glacial pebbles show typical shapes only rarely. Wright (1914, p. 29), on the other hand, noted the abundance of subangular pebbles in glacial deposits and also observed the common occurrence of strial on facetted pebbles. Twenhofel (1926, p. 180) and Coleman (1926, p. XXXVI) were of the opinion that the larger particles in such deposits do tend to have a characteristic shape.

Von Engeln (1930) made a comprehensive study of the forms of glacial pebbles and concluded that "the pebbles should also tend progressively toward some particular shape or shapes". He argued, on theoretical grounds, that the ultimate form so developed would be that of a striated and facetted 'flativon'. His conclusions were supported by the quantitative studies of Wentworth (1936a, 1936b) who stated that "the most characteristic shape, general and marginal, ... is seen to be parallel tabular, with a pentagonal margin".

In the light of the outstanding studies of Von Engeln and Wentworth, the data obtained by the author is of interest. About 5-10% of the pebbles and cobbles in the basal boulder bed shown in plate 3 approximate in form to Von Engeln's "type facetted pebbles" ('pentagonal' cobbles of Wentworth). In the upper boulder bed only about 1-3% are pentagonal in shape. The cross-bedded horizons of the upper boulder bed show a very poor development of the facetted forms and are in general spherical.

Quantitative evaluation of shape characteristics

The forms outlined by Von Engeln and Wentworth are not subject to measurements and though they are very useful in recognizing glacial deposits, they cannot be used for comparison or correlation purposes. A more quantitative approach was made by Wadell (1932) who evaluated shapes of sedimentary particles in terms of their sphericity. He defined sphericity as the ratio of the surface area of a sphere having the same volume as the particle and the total surface area of the pebble itself. In order to overcome the difficulties in the measurement of surface areas of irregular particles, Wadell (1934, 1935) expressed sphericity as $\frac{dn}{Ds}$, where dn is the nominal diameter (diameter of a sphere having the same volume as the pebble) and Ds the diameter of the circumscribing sphere (usually the largest axis of the pebble).

Wadell's method, though very accurate, is time consuming and impracticable where large samples are to be handled. Further, the sphericity values obtained by this method do not give any idea of the actual shape of particles of different shapes having the same sphericity. Such distinction was made by Zingg (1935, p. 54) who used the ratio of the longest (a), the intermediate (b), and the shortest (c) diameters of particles to define the following four shape classes:-

Zingg shape classes	Axial ratios	
I. Oblate spheroid (discoidal)	b/a 2/3	c/b 2/3
II. Spherical (equiaxial)	b/a 2/3	c/b 2/3
III. Bladed (triaxial)	b/a 2/3	c/b 2/3
IV. Prolate spheriod (rod-like)	b/a 2/3	c/b 2/3

Krumbein (1941) has shown that a definite relationship exists between the three diameters of a particle as defined above and Wadell's sphericity indices, and has been able in this way to superimpose curves of equal sphericity on Zingg's chart. The discrepancy in Wadell's method, therefore, can be overcome by using sphericity graphs. An additional advantage in using this method is that Zingg percentages can be directly obtained which constitute an useful information with respect to the shapes of particles.

In the present study the coarse particles of the boulder bed were first classified into Zingg shape classes. Fifty pebbles and cobbles from each horizon of the boulder bed in the different coalfields were randomly selected. The 'a', 'b' and 'c' diameters of each pebble were measured by a wooden sliding-gauge. The ratios b/a and c/b were then computed and the position of each pebble was plotted in a sphericity graph. Particles lying in each shape class were totalled and percentages calculated.

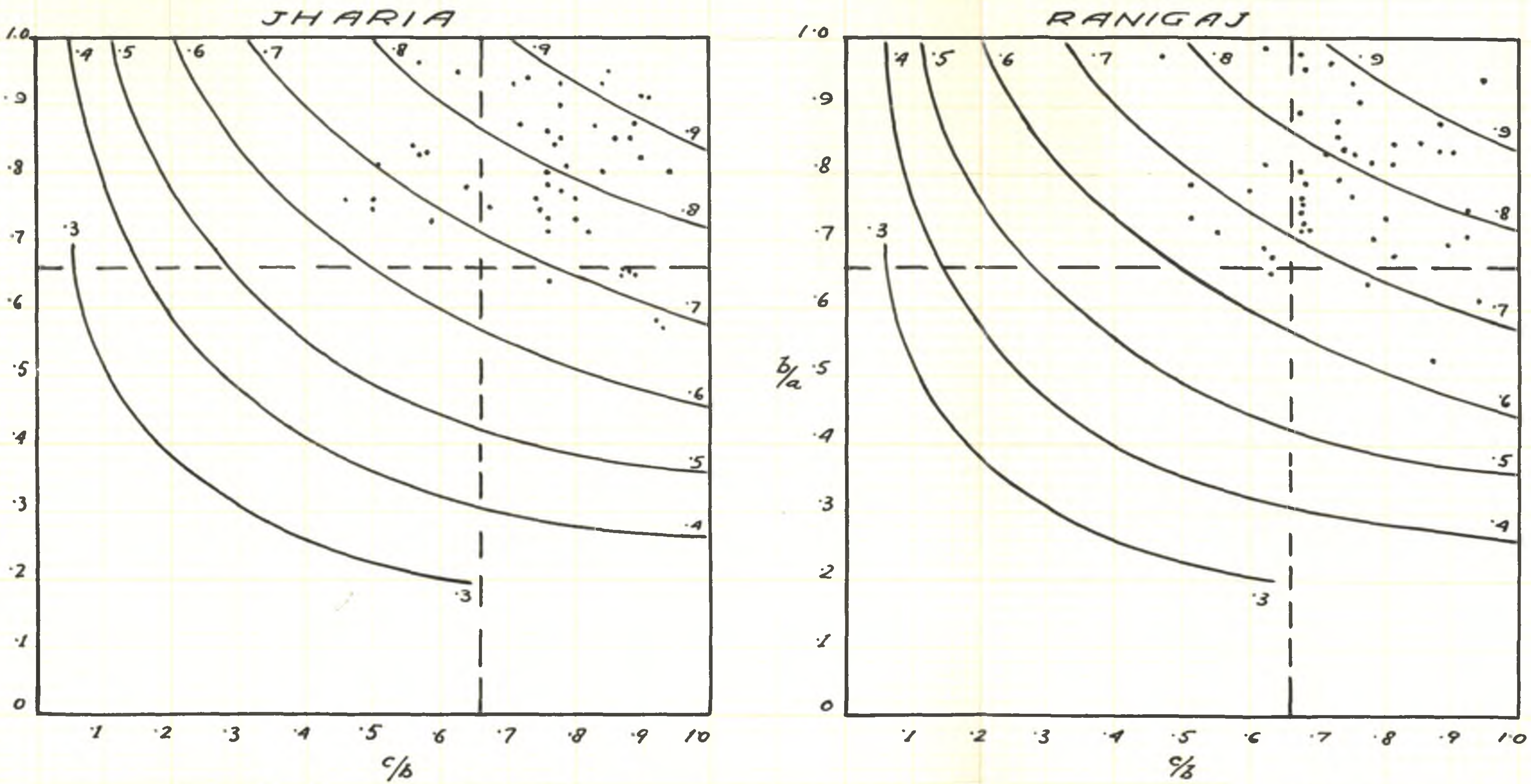
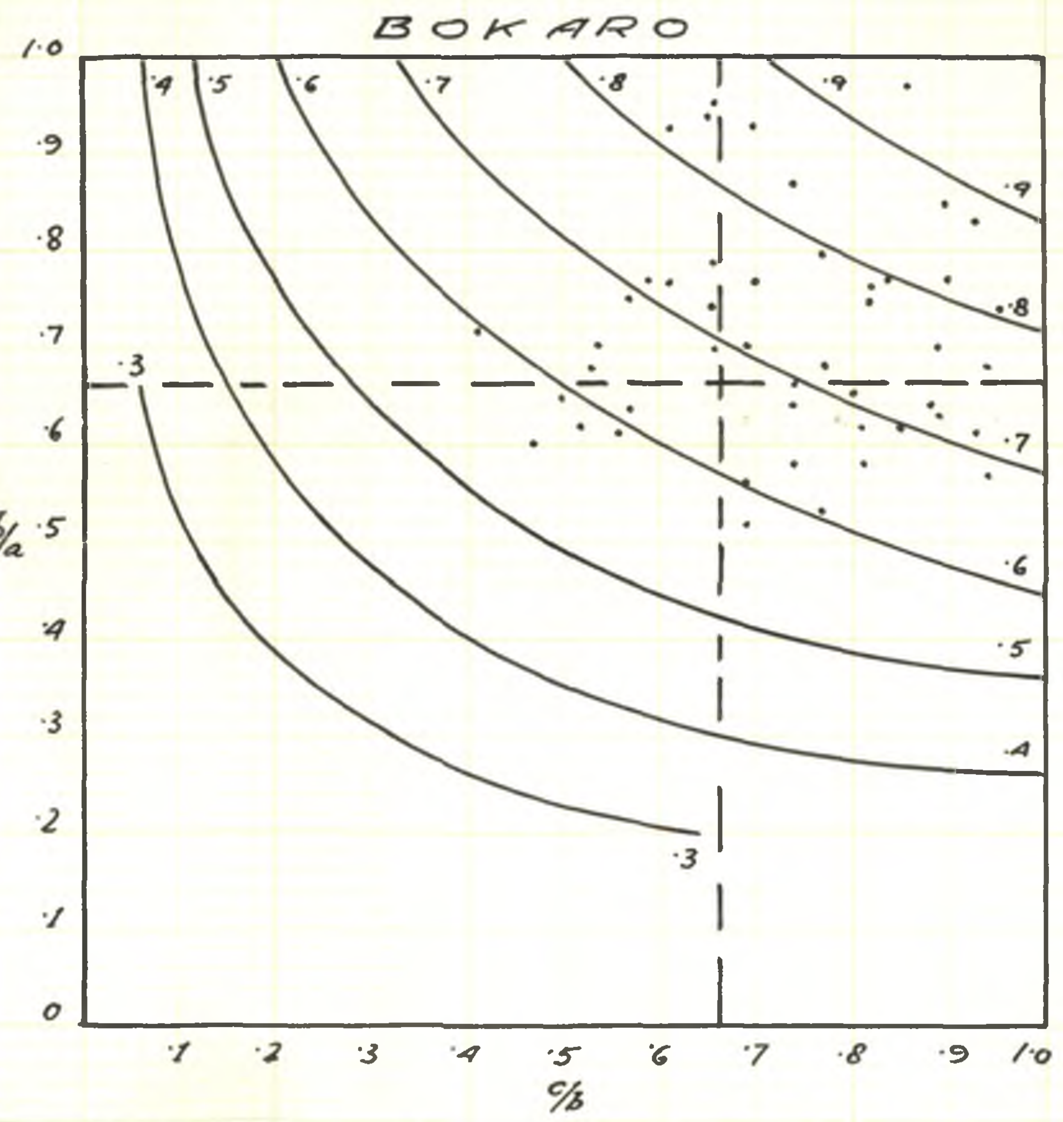
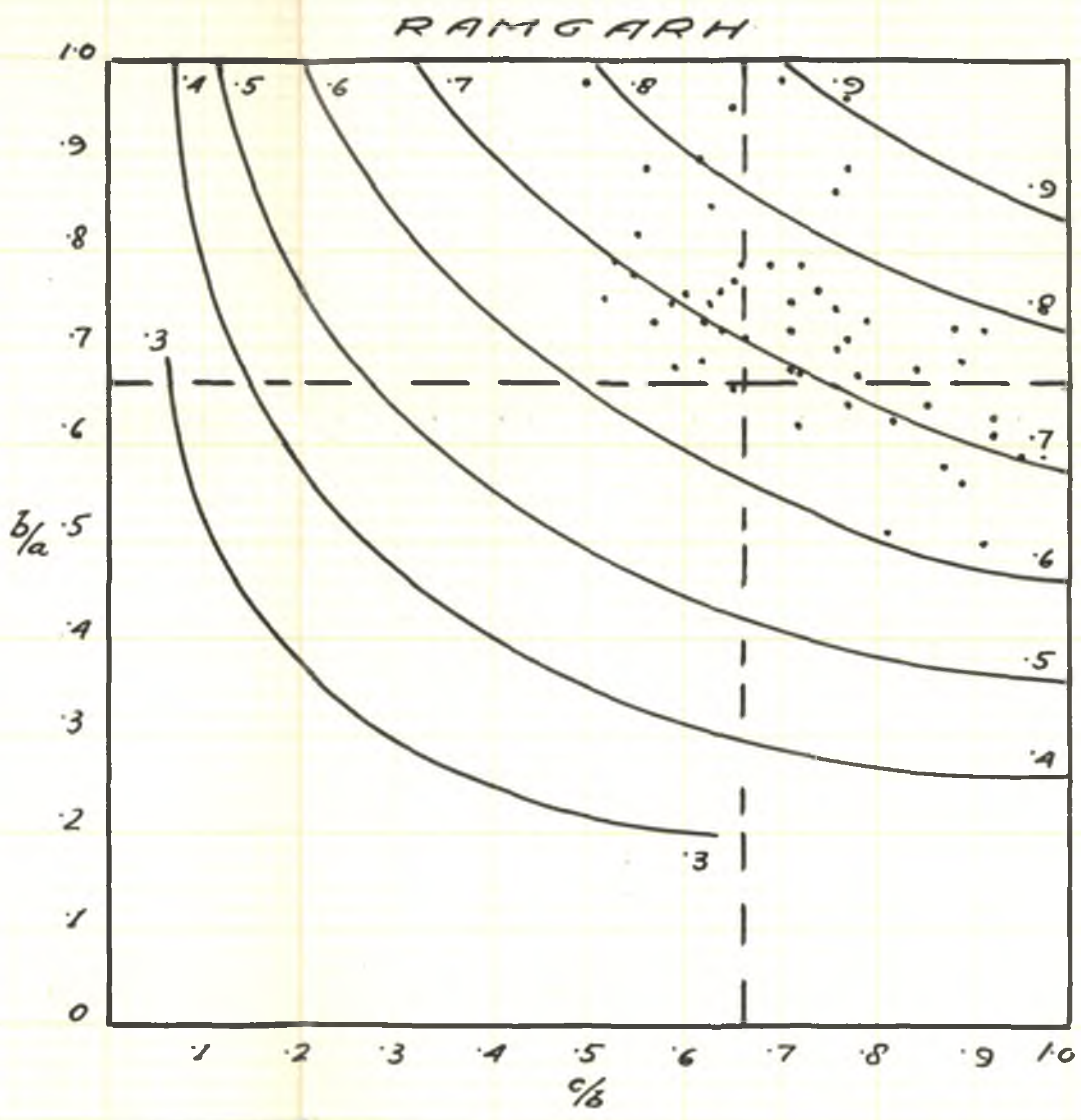
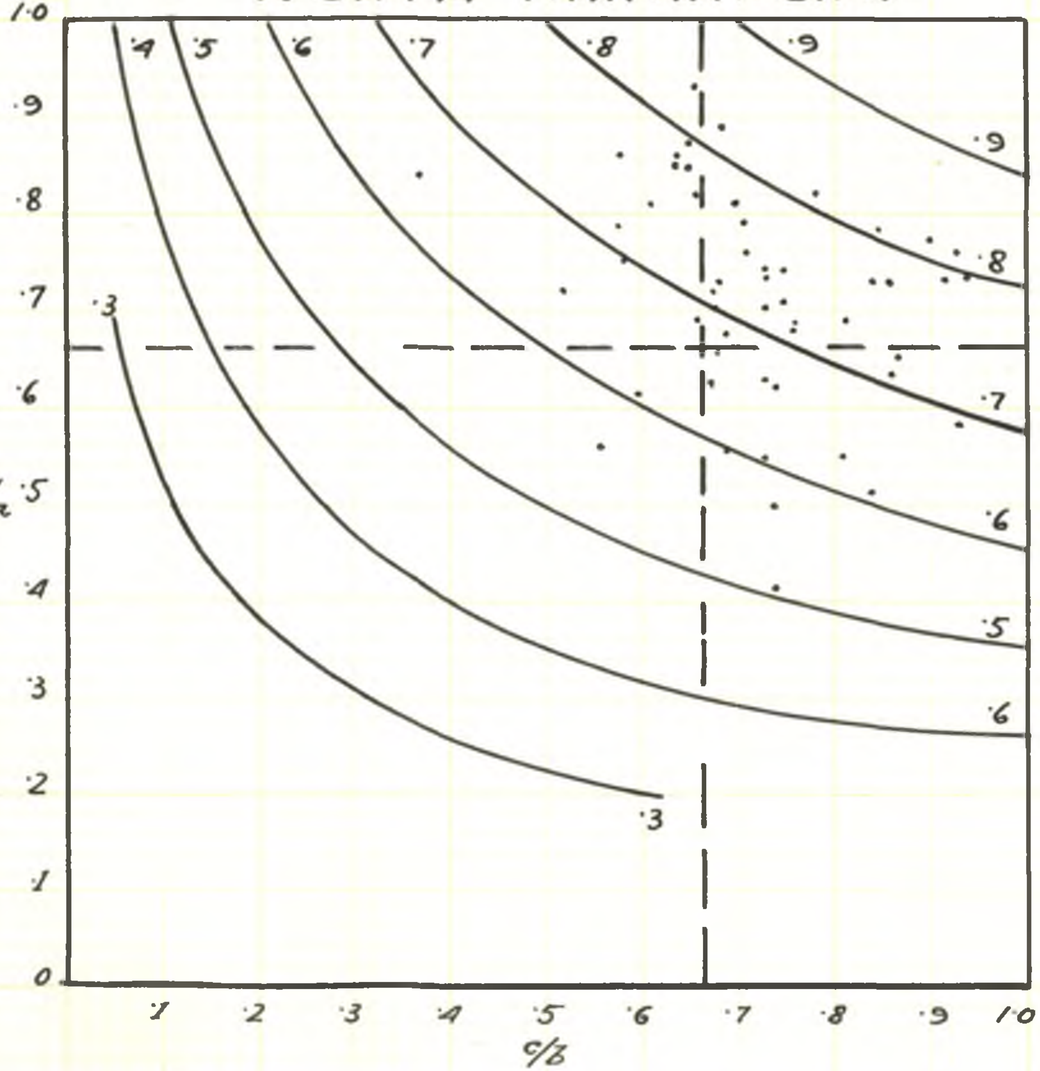


Fig. 2. Sphericity plot of pebbles and cobbles of the basal boulder bed.

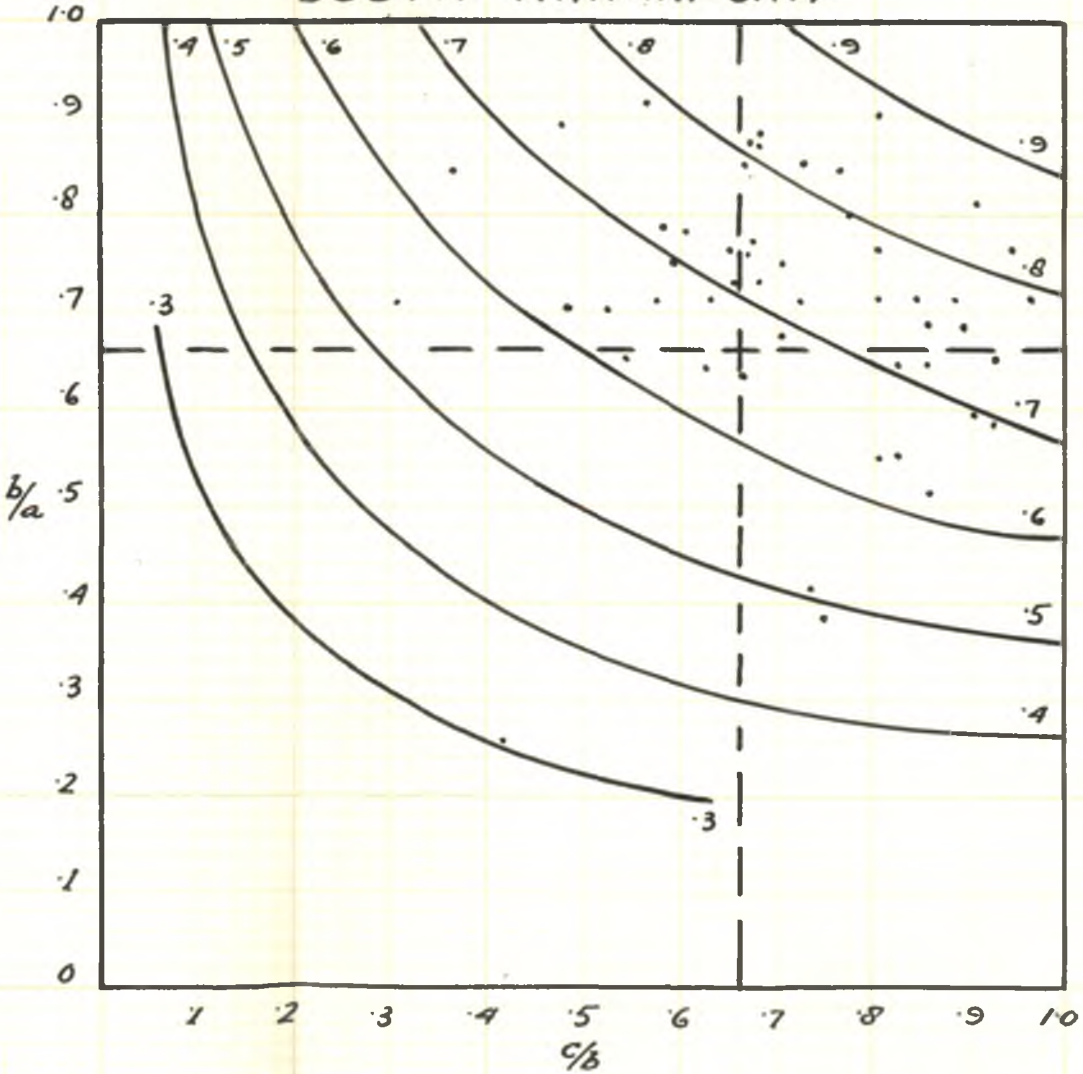

BOKARO
b/a
c/b


RAMGARH
b/a
c/b

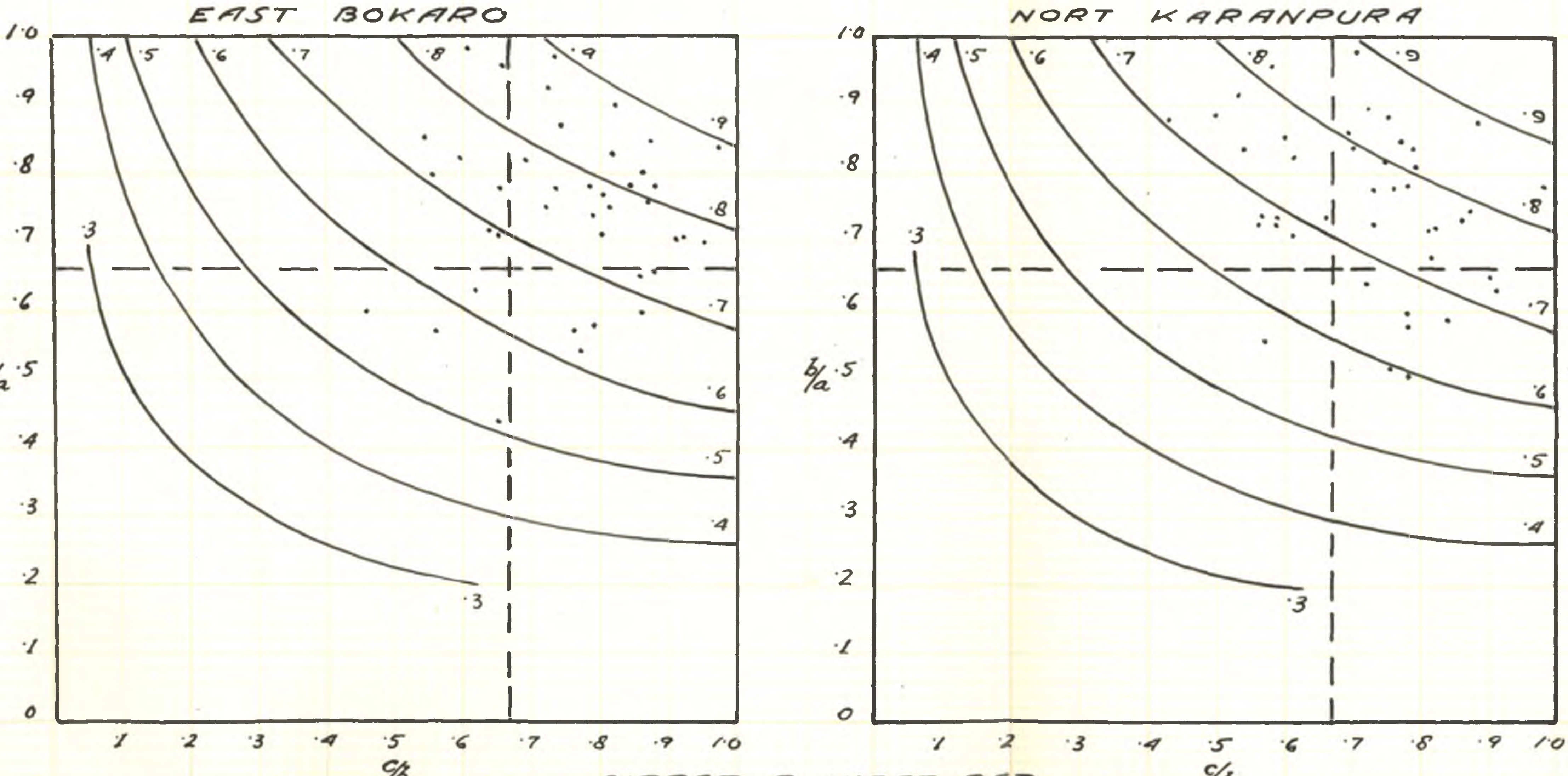
NORTH KARANPURA



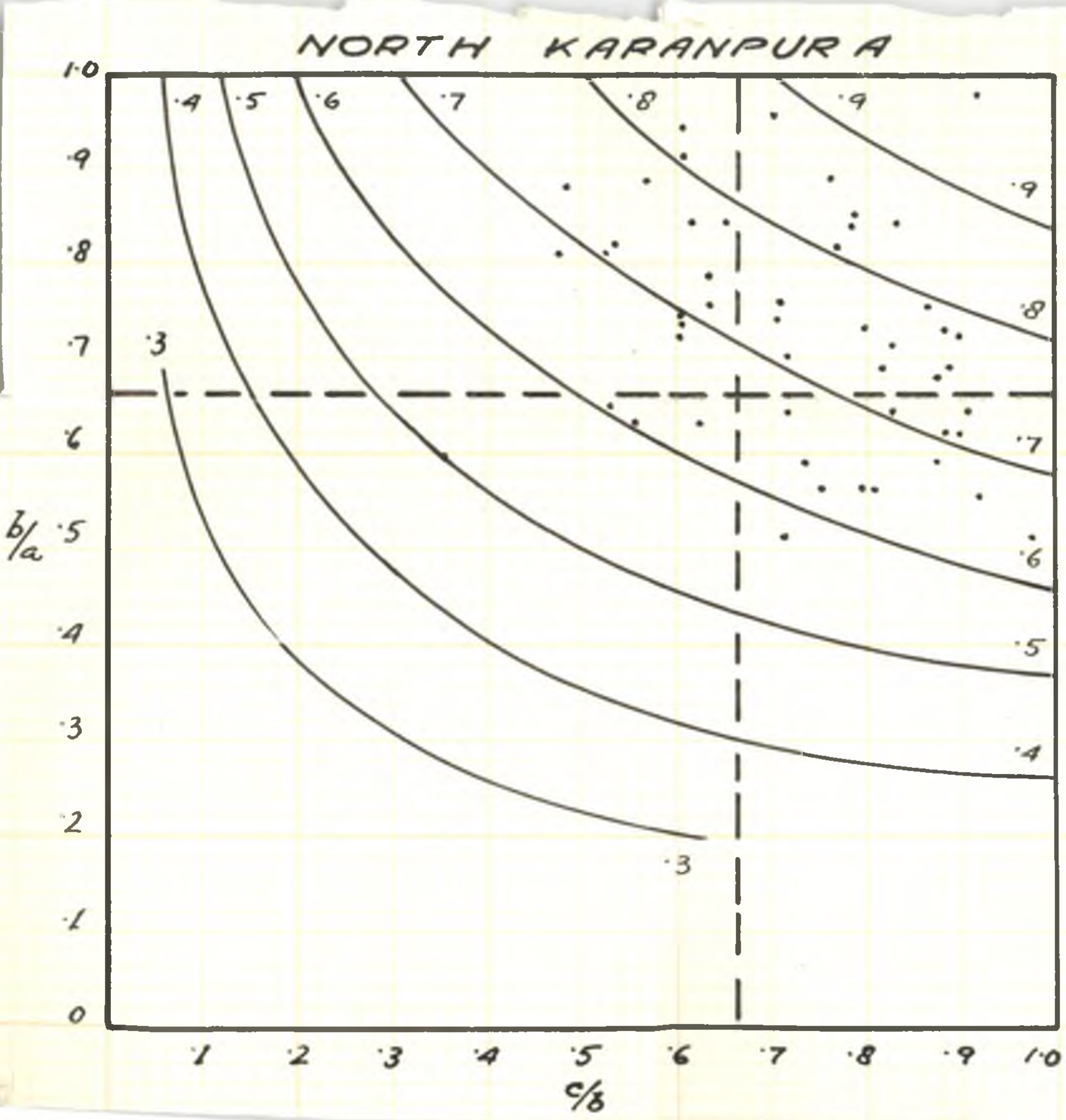
SOUTH KARANPURA

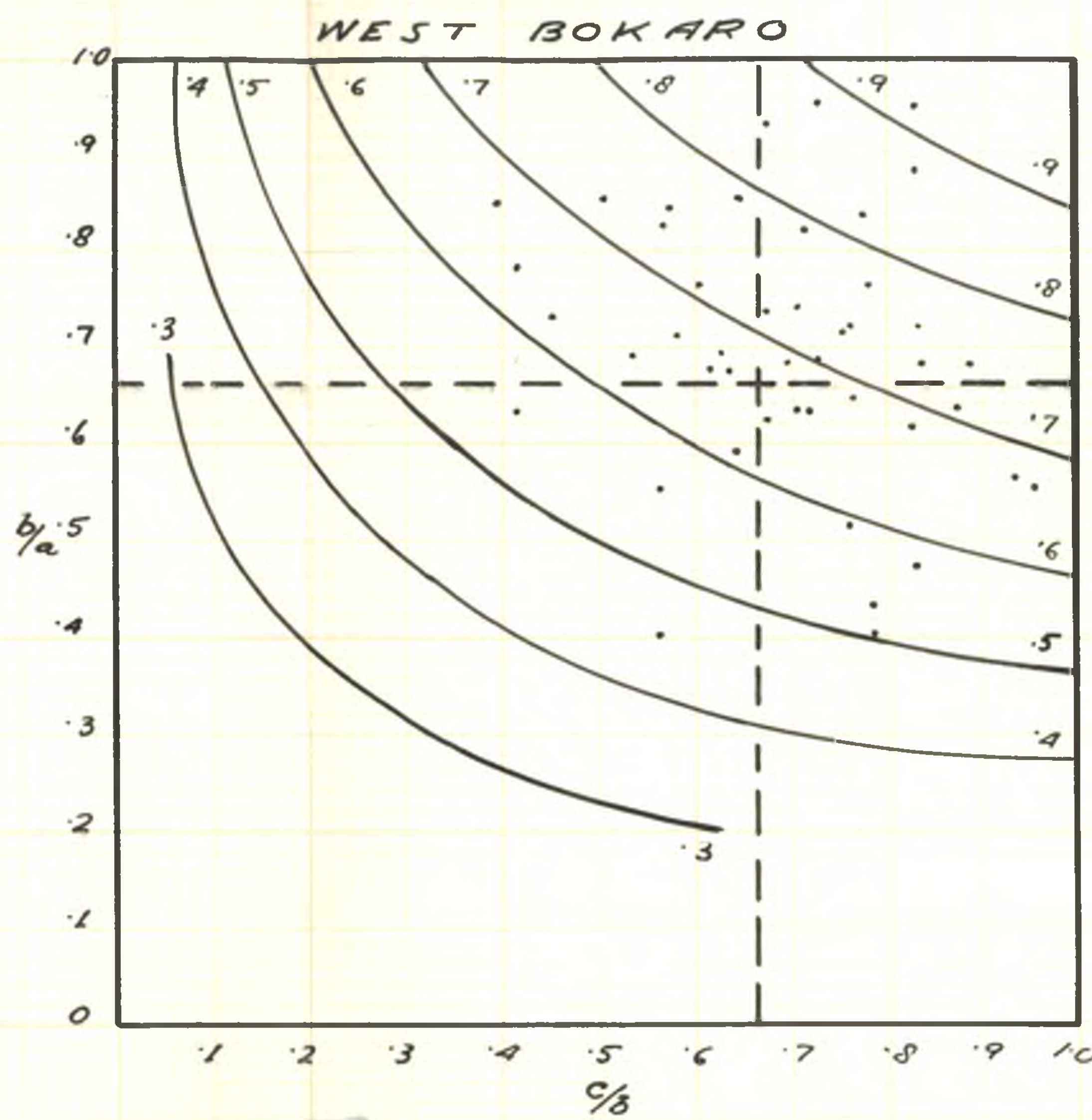


CROSS-BEDDED HORIZONS



UPPER BOULDER BED


NORTH KARANPURA
b/a
c/b


WEST BOKARO
b/a
c/b

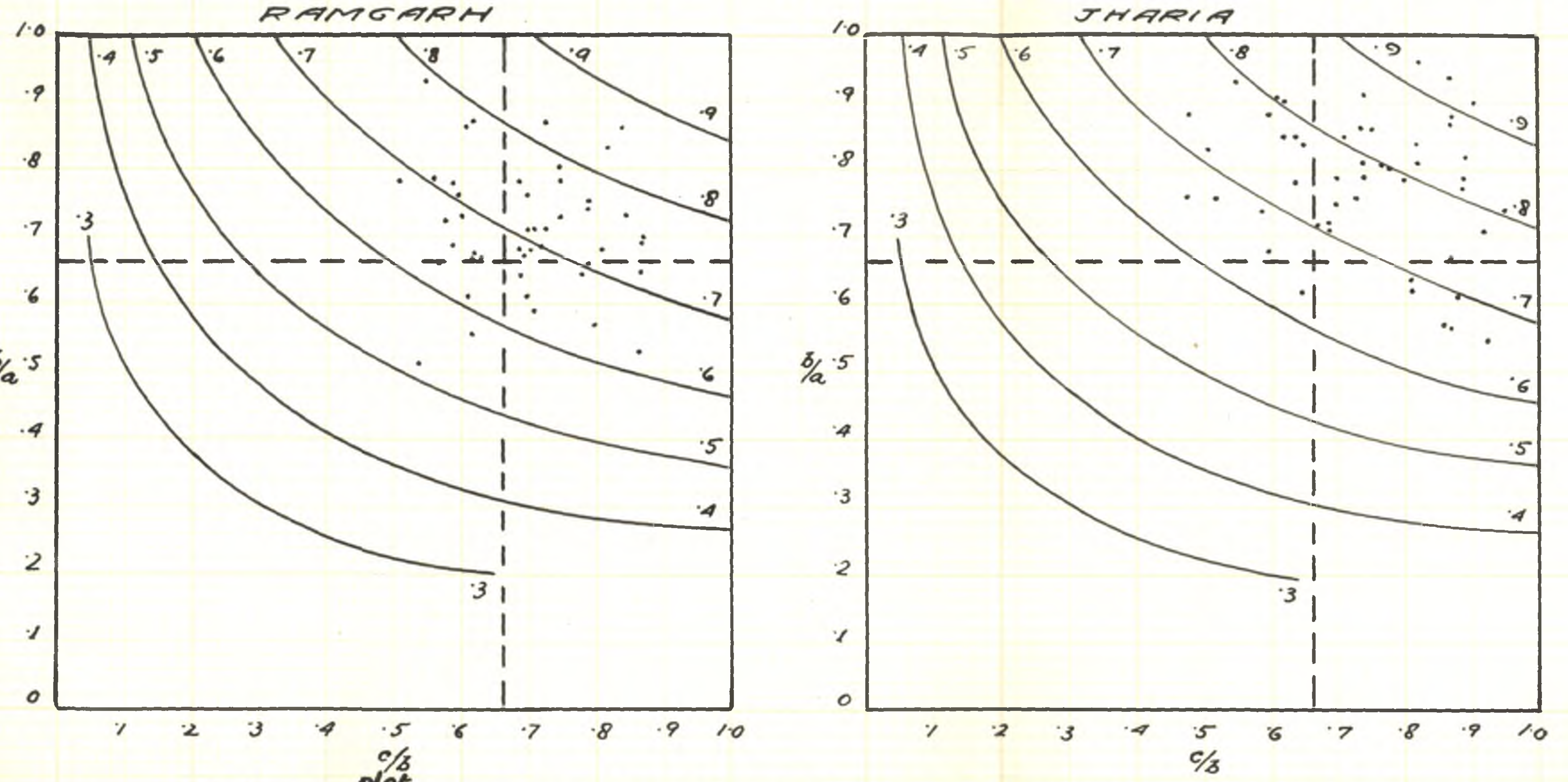


Fig. 3. Sphericity plot of pebbles and cobbles of the upper boulder bed and the cross-bedded horizons.

Figures 2 and 3 show the sphericity plots for the pebbles and cobbles of the basal and upper boulder bed respectively including the cross-bedded horizons of the latter. Table 3 summarises the shape data in terms of the Zingg percentages for each coalfield as obtained from the sphericity plots.

A study of the shape data shows that there is no systematic variation of shapes in the basal boulder bed; on the other hand there are marked and regular changes in the upper boulder bed. The percentage of spherical particles shows systematic increase from west to east from 34% in the North Karanpura coalfield to 58% in the Jharia coalfield. There is an equally regular decrease in the percentage of prolate particles in the same direction, while the oblate and triaxial pebbles and cobbles show no special preference. The cross-bedded horizons of the upper boulder bed show the same trend but the data is not sufficient for making any generalization.

Table 4 gives the frequency distributions of sphericity values, as determined from the sphericity plots, in terms of the arithmetic mean

TABLE 4: SPHERICITY VALUES OF PEBBLES AND COBBLES

COALFIELD	Basal boulder bed		Upper boulder bed		Cross-bedded horizons	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
North Karanpura	0.722	0.081	0.728	0.081	0.730	0.083
South Karanpura	0.718	0.088	.....	.....	.....	.....
Bokaro	0.731	0.098	0.696	0.096	0.752	0.086
Ramgarh	0.726	0.068	0.700	0.071	.....	.....
Jharia	0.778	0.082	0.764	0.081	.....	.....
Raniganj	0.770	0.083	.....	.....	.....	.....

and standard deviation. There does not appear any significant or regular variation in the sphericity values of the particles in the different horizons of the boulder bed in a given coalfield nor in the same horizon in different coalfields. However, the particles of the basal boulder bed are, in general, more spherical than those of the upper bed. The standard deviations of the frequency distribution, show no definite relation to mean sphericity.

A comparison of Tables 2 and 4 show that no relationship whatsoever exists between roundness and sphericity of particles in the basal boulder bed. The correlation between the two is rather poor in the upper bed and its cross-bedded horizons.

S U R F A C E   T E X T U R E S

Pettijohn (1957, p. 68) defines surface textures of particles as the "minor features of the grain surface, independent of size, shape or roundness". These features are generally impressed on the particles of clastic deposits during transportation but may also be due to post-depositional changes. As the surface markings are superficial in character, even a small transport is enough to erase them and therefore the presence of such features on the surface of particles shows clearly that much abrasion and, therefore, long transport has not taken place after their deposition.

It was noted by earlier workers (Fedden, 1875, p. 18; Oldham, 1922, p. 2; Fox, 1930, p. 103) that the surface of some of the pebbles and cobbles in the boulder bed bear striations and scratches. But no attempt was made by them to study this characteristic in detail.

Of the various minor features included under the heading of 'surface textures', the most common and important are the striations and grooves on the surface of pebbles and cobbles. The prominence and distinctiveness of these markings varies with the composition and texture of the particles. Coarse grained particles like those of granite, pegmatite, gneiss, mica schist and conglomerate, bear no such markings; pebbles of fine grained rock types usually show striations and grooves on their surface. Fine grained quartzites show clear but narrow and superficial striae while greenstone pebbles exhibit prominent and comparatively deeper scratches.

The striation pattern on the pebbles and cobbles is simple and consists of parallel or sub-parallel grooves which, in turn, are parallel to the long axis of the stones. This characteristic was also noted by Wentworth (1936a, p. 96) on cobbles of Wisconsin morainal deposits. In terms of transportational dynamics, this parallelism between the markings and the long axes is interesting. Striations are produced on the pebbles and cobbles in a direction parallel to the ice movement and since these have been found to be parallel to the long axes, it follows that at least during transport the long axis of particle tends to be parallel to the direction of ice movement. Random and grid patterns are conspicuously absent from the surface of pebbles and cobbles of the boulder bed.

The lateral facets of some of the 'modified' pebbles and cobbles are also occasionally striated. The striae on such surfaces are, however, very faint, pointing downward towards the prow, and are not so well developed as those on the basal soles. According to Von Engeln (1930, p. 14) the markings on the lateral facets are produced as a result of differential movement between the pebbles and the 'debris laden bottom ice'.

CHAPTER IV

PETROGRAPHY OF THE FINE FRACTION

The "fine fraction" of the boulder bed has been studied in detail with respect to its mechanical composition, micropetrology and heavy mineral content with a view to trace the provenance of the boulder bed and also to correlate its various horizons in the different coalfields of the Damodar Valley. This fraction constitutes the material smaller than 4 mm. in diameter.

The study of this fraction has not received much attention by earlier workers and no quantitative data in regard to its physical attributes is available. In view of this fact the present investigation may substantially add to our knowledge regarding the conditions of sedimentation during the formation of the Talchir boulder bed.

M E C H A N I C A L   C O M P O S I T I O N

Field Sampling

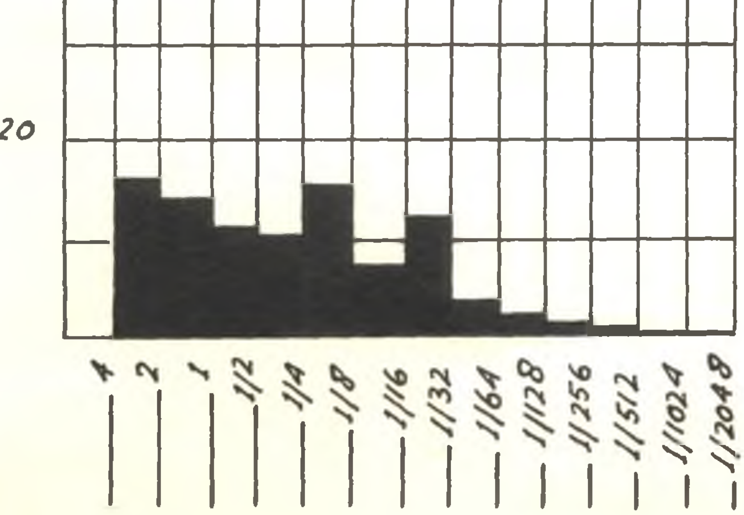
Eighty samples of the fine fraction of the boulder bed were collected from unweathered zones from different localities for grain size analyses. Most of the samples were collected from outcrops in stream beds, but wherever possible, samples were collected from vertical cuttings of streams. The various localities from where samples were obtained are shown in Fig. 1.

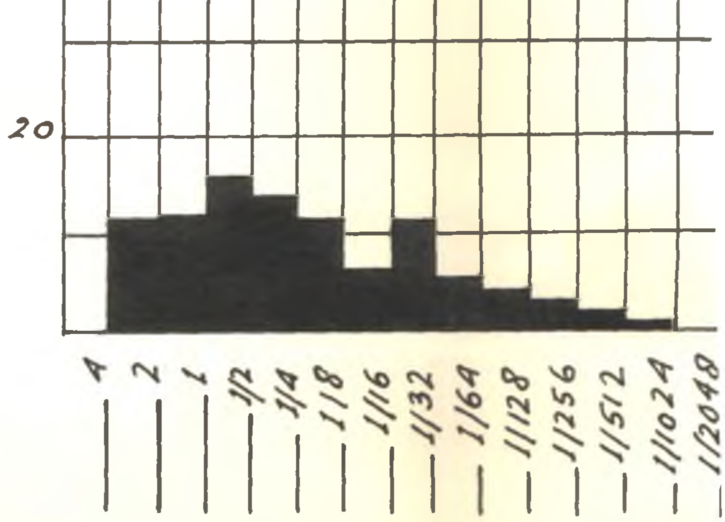
The sampling methods outlined by Krumbein and Pettijohn (1938) were generally followed for obtaining representative samples. Five widely spaced "compound" samples of the fine fraction were collected from each locality, each sample being obtained by combining four closely spaced "spot" samples so as to eliminate, as far as possible, the chances of incorporating such variations that may be present but are not apparent to the unaided eye. About 10 lbs. of each sample were securely packed and labelled for further investigation in the laboratory.

Analytical Procedure

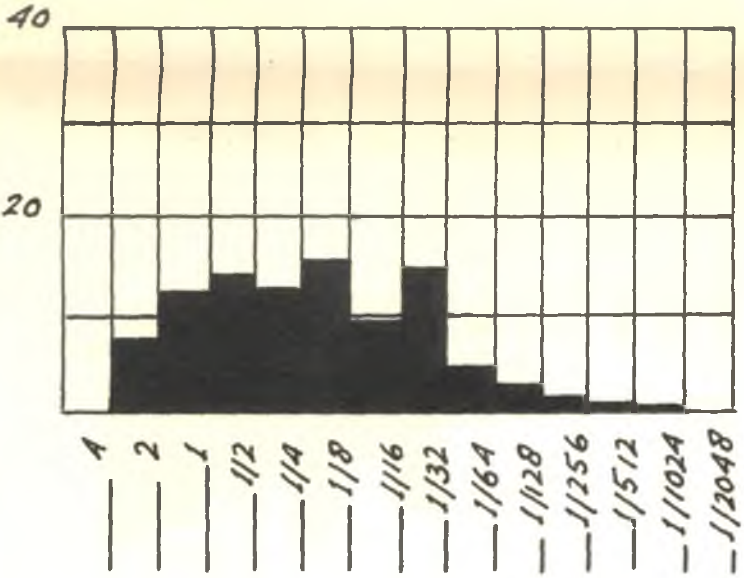
About 2 lbs. of the air-dried field sample were placed on thick, smooth packing paper on a wooden board and crushed gently by a wooden rolling pin till reasonably small aggregates were obtained. Particles larger than 4 mm. were removed by hand picking during the earlier stages of crushing and later by sieving the whole material through a 4 mm. sieve. A representative sample was ultimately obtained by repeatedly passing the material so obtained through a Jones type sample splitter till about 200-400 gms. of the sandy matrix and 40-100 gms. of the silty or clayey matrix were left.

Each sample was accurately weighed on a chemical balance and according to the size of the sample, soaked in a measured amount (100-200 cc.) of N/100 sodium oxalate solution. The time allowed for soaking varied according to

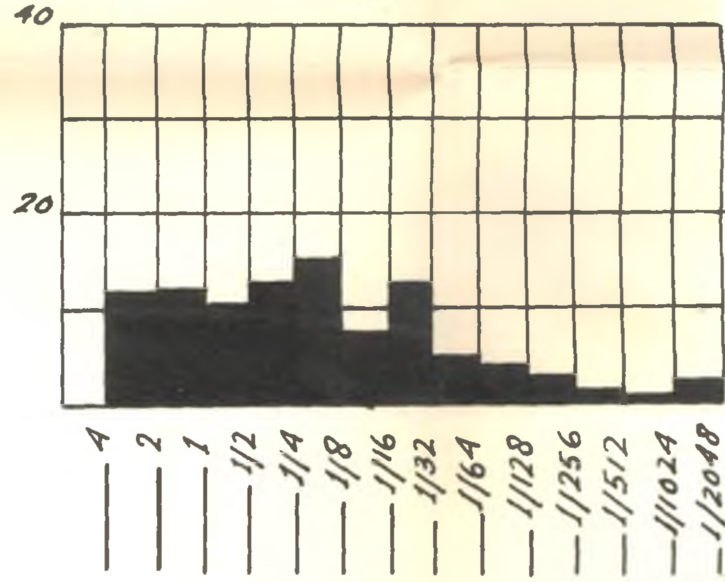




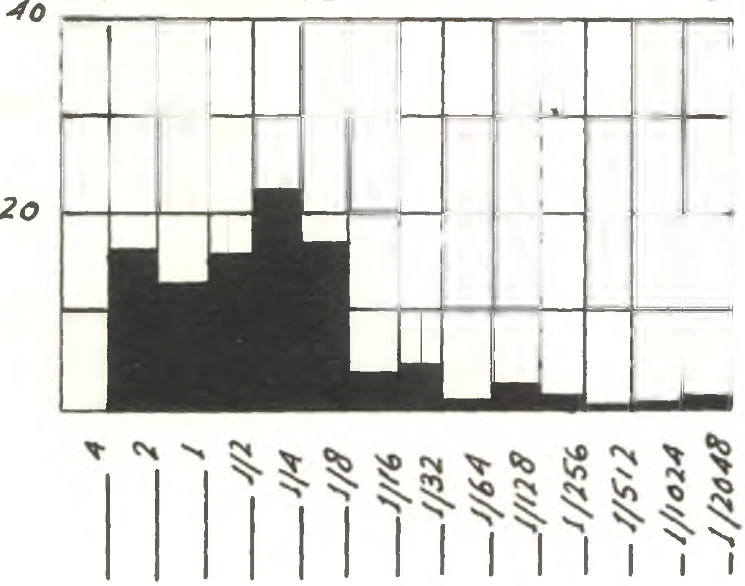
c. AVERAGE OF SAMPLES 46-50



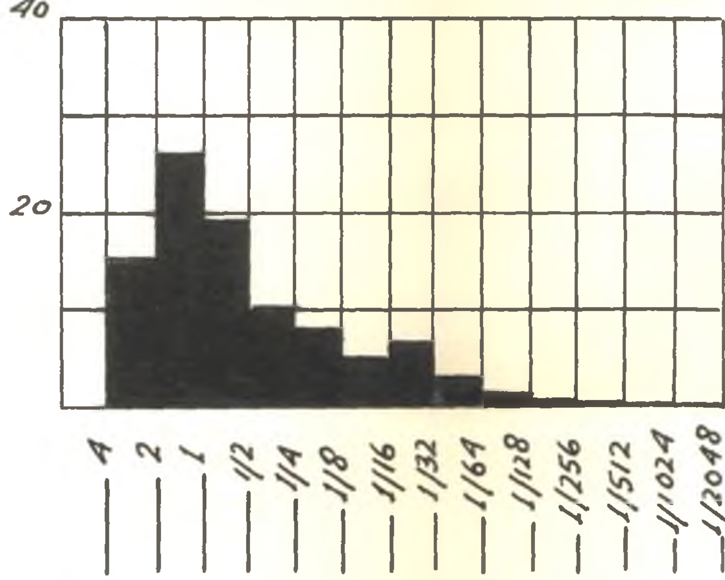
d. AVERAGE OF SAMPLES 56-60



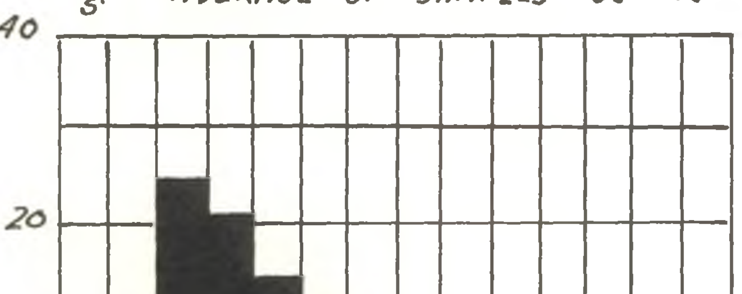
e. AVERAGE OF SAMPLES 11-15



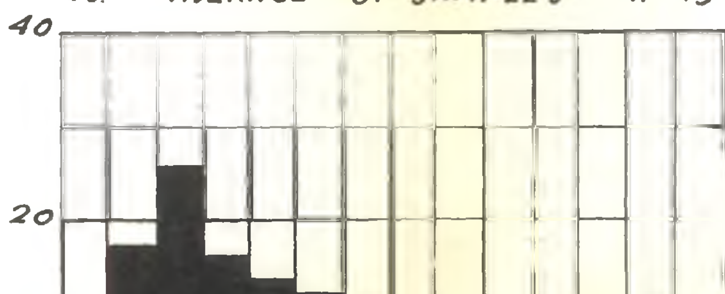
f. AVERAGE OF SAMPLES 31-35

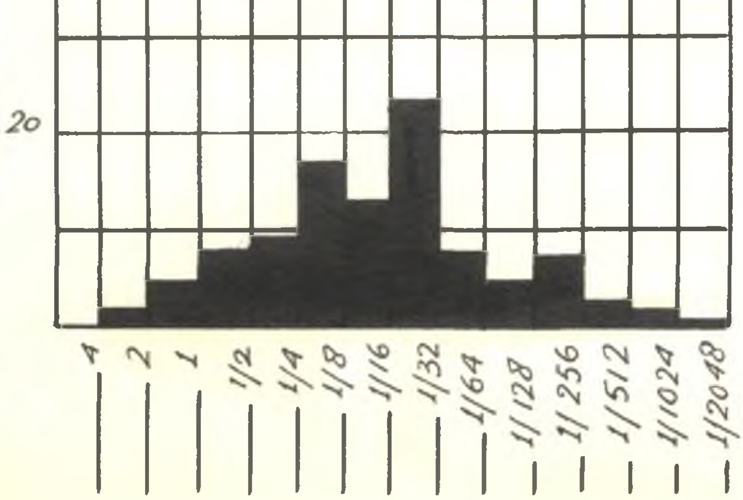


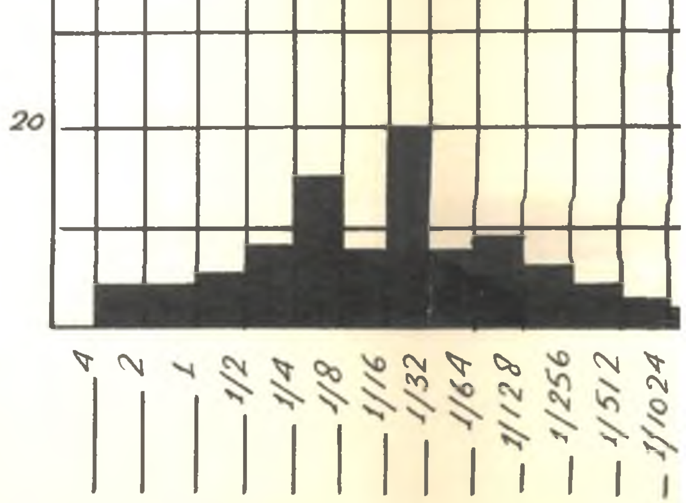
g. AVERAGE OF SAMPLES 36-40



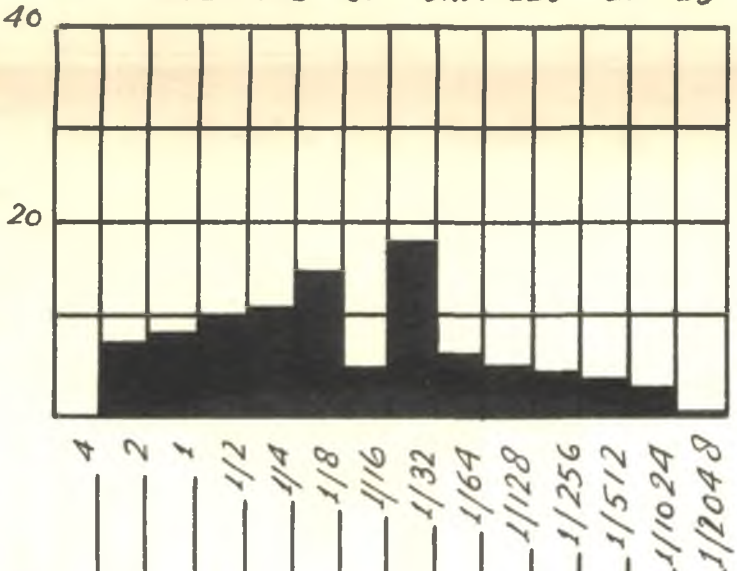
h. AVERAGE OF SAMPLES 71-75



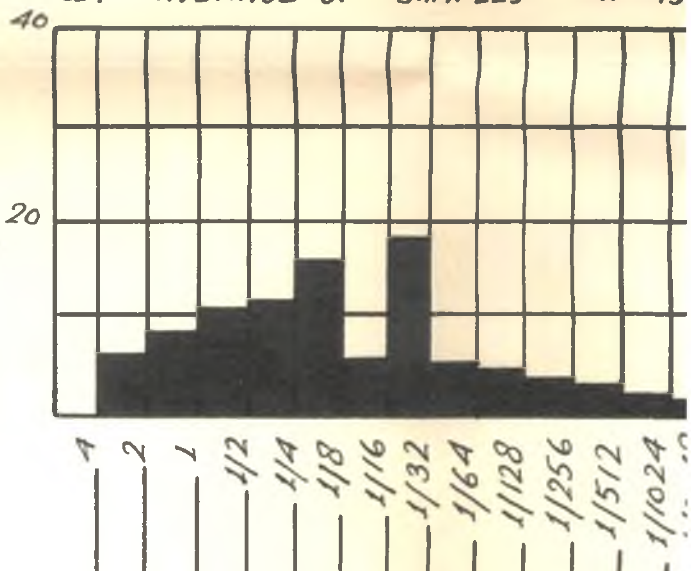




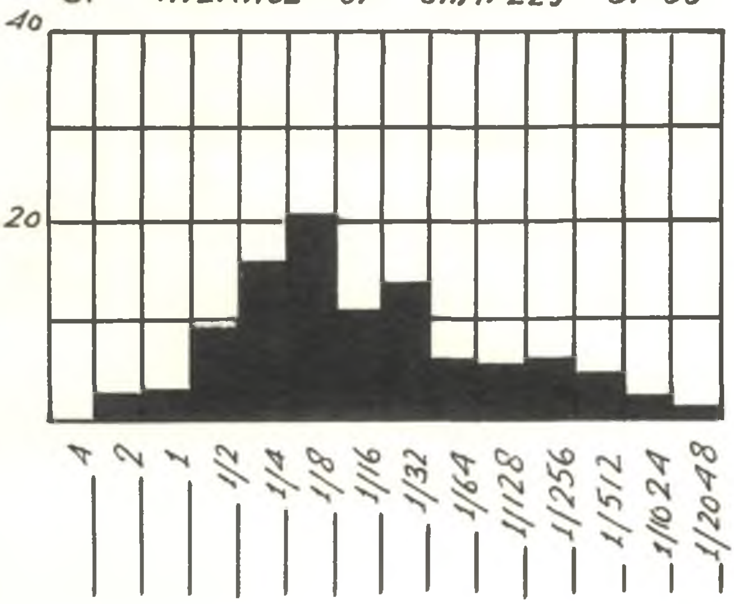
c. AVERAGE OF SAMPLES 21–25



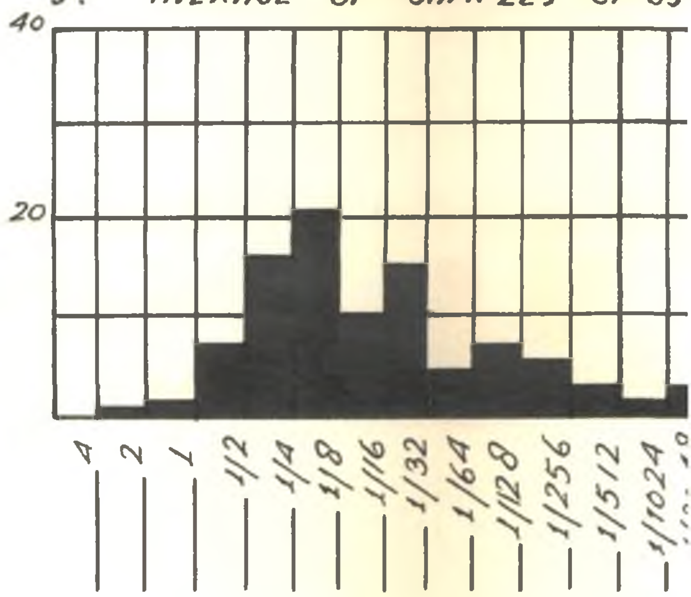
d. AVERAGE OF SAMPLES 41–45



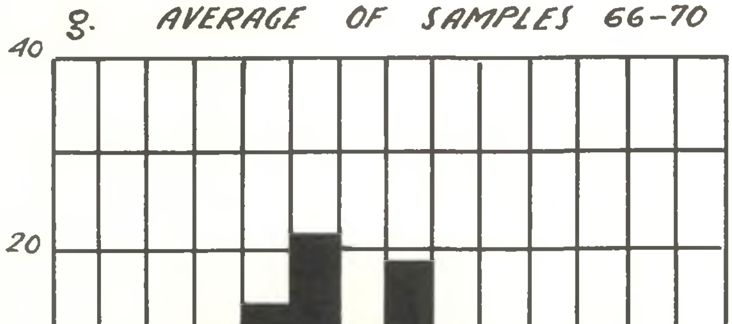
e. AVERAGE OF SAMPLES 51–55



f. AVERAGE OF SAMPLES 61–65



g. AVERAGE OF SAMPLES 66–70



h. AVERAGE OF SAMPLES 76–8

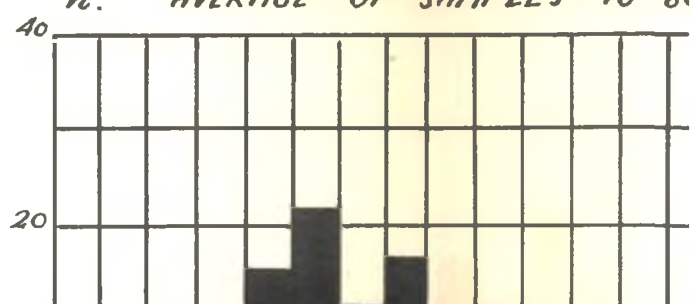


TABLE 8: AVERAGE MECHANICAL COMPOSITION OF THE TALCHIR BOULDER BED

L A S S (mm.)	1 1-5	2 6-10	3 11-15	4 16-20	5 21-25	6 26-30	7 31-35	8 36-40	9 41-45	10 46-50	11 51-55	12 56-60	13 61-65	14 66-70	15 71-75	1[illegible] 76-
	1.47	16.61	16.09	4.34	7.45	11.99	15.19	8.91	6.65	7.66	2.71	11.53	1.06	0.56	17.85	1.
	4.40	14.48	12.65	4.32	8.54	12.12	25.91	24.40	8.60	12.51	2.75	11.96	1.82	1.05	25.48	2.
/2	7.59	12.00	15.57	5.89	10.05	15.87	19.12	20.83	10.68	14.20	9.38	10.53	7.83	5.27	16.27	5.
-1/4	8.93	10.84	22.81	8.67	10.88	13.83	10.42	14.82	11.81	13.16	15.90	12.76	16.22	14.37	14.15	16.
-1/8	16.85	16.06	16.44	15.15	14.59	11.50	8.06	10.94	15.84	15.77	20.38	14.97	20.41	21.59	12.65	21.
-1/16	12.65	7.82	4.23	7.99	5.23	6.23	5.31	5.04	5.91	9.20	10.84	7.46	10.02	10.89	5.12	11.
6-1/32	23.25	12.18	4.65	20.05	17.94	11.41	6.25	4.78	18.14	15.08	13.71	12.59	15.28	18.76	3.00	16.
2-1/64	7.24	3.91	1.21	7.96	6.49	5.62	3.11	2.73	5.68	4.33	6.17	4.77	5.18	7.14	1.49	5.
4-1/128	4.73	2.15	2.66	9.56	5.68	4.28	2.17	2.01	4.95	2.87	5.60	4.29	7.89	6.08	0.96	7.
28-1/256	7.23	1.48	1.53	6.22	4.71	3.35	1.47	1.13	3.99	1.63	6.21	2.89	5.82	4.10	0.69	4.
56-1/512	2.50	1.27	0.56	4.59	4.11	2.29	1.38	1.45	3.77	1.14	4.59	1.81	3.15	4.85	0.80	4.
12-1/1024	1.72	0.71	0.82	3.15	3.11	0.90	1.23	1.05	2.81	0.97	2.47	1.79	2.22	3.05	0.68	3.
024-1/2048	0.72	0.38	1.32	2.13	0.63	0.42	1.14	0.46	1.89	0.89	1.26	2.23	3.42	2.34	0.86	2.

the nature of the sample. Most samples crumbled after they were soaked for 24 hours but some required two to four days of soaking before they could be properly disaggregated. All the samples from the Bhera river section in the eastern part of the Ramgarh coalfield and a few from the upper boulder bed in the West Bokaro and North Karanpura coalfields defied all attempts to disaggregate and were not analysed.

The soaked sample was then rubbed with a rubber pestle till disaggregation was complete and during this operation distilled water with a concentration of N/100 sodium oxalate was occasionally added, care being taken not to increase the total volume of the suspension by more than about 400 cc. The suspension was then tested for complete dispersion under the microscope and passed through a 240 mesh B.S.S. sieve (aperture opening 0.066 mm.) kept on a metal funnel of 8½ inches diameter and the material which passed through was collected in a 1000 cc. beaker. The residue was repeatedly washed with N/100 sodium oxalate solution till clear liquid passed through the funnel. At this stage the total volume of the suspension was usually kept at about 800 cc. and this was then transferred to a graduated cylinder having a capacity of 1000 cc.

The coarse residue on the 240 mesh sieve after being dried and weighed was shaken for twenty minutes on an AIMIL sieve shaker with the B.S.S. sieves arranged from top to bottom in the decreasing order of their aperture opening. Table 5 shows the sieves used with their aperture openings in millimeters and the corresponding Wentworth grade limits (Wentworth 1922b, p. 382). It is to be noted that the millimeter equivalents of numbers

16, 60, 120 and 240 mesh sieves do not correspond exactly with Wentworth

TABLE 5: SIEVES USED AND THE CORRESPONDING WENTWORTH GRADE LIMITS

B.S.S. Mesh No.	Sieve opening (mm.)	Wentworth class limits (mm.)	Difference (mm.)
5	4.000	4.000	0.000
10	2.000	2.000	0.000
16	1.003	1.000	0.003
30	0.500	0.500	0.000
60	0.251	0.250	0.001
120	0.124	0.125	0.001
240	0.066	0.063	0.003

grade limits but the differences are so insignificant that they can be safely ignored.

The fraction caught on each sieve was then weighed separately and its weight percentage calculated.

The material passing through the 240 mesh sieve and caught on the pan was added to the suspension in the litre-graduate and the volume of the suspension was made up to exactly 1000 cc. by adding distilled water with a concentration of N/100 sodium oxalate. The suspension was then analysed for the finer grades by the pipette method (Krumbein and Pettijohn, 1938, p. 166).

The pipette method consists of first thoroughly shaking the suspension by a stirrer and then taking out a 20 cc. sample with the help of a pipette at given intervals from a depth of 10 cm. from the surface of the suspension in all cases except for sizes less than 1/1024 mm. for which the samples were drawn from a depth of 5 cm.

TABLE 6: TIME SCALE FOR PIPETTE ANALYSIS
(Modified from Twenhofel & Tyler, 1941, p. 54)

Diameter (mm.)	Depth from which sample drawn (cm.)	Time Hr.	Min.	Sec.
1/32	10	0	1	56
1/64	10	0	7	44
1/128	10	0	31	00
1/256	10	2	3	00
1/512	10	8	10	00
1/1024	5	16	21	00
1/2048	5	65	25	00

TABLE 7: MECHANICAL ANALYSIS OF THE TALCHIR BOULDER BED

	RTH			KARANPURA				COALFIELD						SOUTH	KARANPURA		COALF
	boulder	bed		Upper	boulder		bed		Cross-bedded			horizon		Basal	boulder		bed
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
5	2.71	2.62	1.56	16.35	15.94	17.13	16.88	16.72	12.17	17.78	17.45	16.40	16.64	5.56	3.53	2.48	5.12
6	7.64	9.12	3.23	13.86	13.40	16.03	15.04	14.09	10.41	12.51	12.72	13.23	13.90	5.59	3.56	2.49	5.47
4	10.62	11.96	9.17	11.44	11.99	11.79	12.59	12.21	14.44	14.11	13.98	19.99	15.32	6.34	6.29	6.59	6.10
5	8.98	10.17	10.38	10.88	11.25	10.96	11.11	9.99	23.95	21.87	22.42	22.17	22.64	8.62	7.87	7.80	9.61
1	13.67	14.02	16.43	14.07	15.49	16.65	17.32	16.76	18.47	16.93	16.37	17.55	15.39	15.39	13.72	15.08	14.76
1	9.08	9.12	12.62	8.39	7.59	6.55	7.78	8.81	4.78	4.29	3.91	3.81	4.35	9.51	7.89	10.61	6.1
4	20.12	20.10	22.10	13.25	17.55	11.87	11.97	12.27	4.47	5.44	4.81	5.01	5.52	19.79	17.58	21.26	20.5
4	9.37	7.40	8.32	4.13	3.68	4.00	3.78	3.96	1.45	0.98	1.12	1.11	1.39	7.21	8.51	9.29	7.8
4	5.56	5.36	4.17	2.89	3.03	1.56	1.43	1.84	3.07	2.30	2.64	2.82	2.50	8.04	10.32	9.99	9.0
3	5.02	3.13	7.50	2.09	2.07	1.00	1.00	1.22	1.70	1.27	1.57	1.72	1.41	5.09	8.71	6.41	5.4
4	2.80	2.23	2.17	1.64	1.76	0.98	0.89	1.10	0.73	0.25	0.78	0.53	0.49	3.67	5.99	3.50	5.1
5	2.45	1.91	2.00	0.70	0.36	0.82	0.81	0.85	1.10	1.04	0.77	0.68	0.51	3.14	3.33	3.15	2.9
5	1.14	1.36	0.32	00.50	0.18	0.66	0.40	0.17	1.98	1.23	1.46	0.98	0.94	1.96	2.78	2.35	1.8

TABLE 7: MECHANICAL ANALYSES OF THE TALCHIR BOULDER BED (CONTINUED)

	WEST			BOKARO				COALFIELD							EAST	BOKARO		COALFIE
	boulder	bed		Upper		boulder	bed		Cross-bedded			horizon			Cross-bedded			horiz
	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	
39	6.42	7.99	8.27	11.45	13.58	12.01	12.71	10.22	14.11	16.86	13.28	16.37	15.34	8.45	9.69	7.73	10.2	
18	8.79	9.01	9.58	11.30	13.76	12.52	13.03	10.01	23.29	25.22	28.25	26.28	26.53	22.56	24.70	25.62	24.5	
61	9.02	10.50	10.43	14.72	15.52	16.73	15.82	16.54	20.91	19.36	17.04	18.83	19.48	21.50	22.10	20.48	20.2	
82	10.22	11.27	10.98	14.46	14.59	13.49	12.97	13.72	10.87	9.97	10.13	11.27	9.87	13.93	14.68	14.71	15.7	
91	13.89	14.82	14.72	12.61	11.32	10.74	10.87	11.96	8.27	8.02	8.31	7.85	7.81	10.89	9.63	11.29	11.6	
05	4.90	3.26	3.04	5.61	5.25	7.35	6.09	6.87	4.49	4.31	5.11	4.02	4.65	5.01	4.42	4.09	6.0	
09	19.29	17.50	20.01	19.14	9.86	10.89	10.53	12.62	7.45	6.56	5.01	6.23	6.00	7.05	2.17	6.63	2.8	
49	6.79	6.23	5.52	4.72	4.61	7.25	5.29	6.23	3.00	2.71	3.25	3.72	2.89	3.47	1.83	2.56	2.2	
45	5.82	4.79	4.82	4.91	4.66	3.98	3.55	4.29	2.55	2.18	2.13	1.89	2.10	2.42	1.91	1.82	2.0	
49	4.85	4.24	5.70	4.15	4.00	2.89	3.36	2.37	1.02	1.28	2.17	1.45	1.44	1.95	0.17	0.57	1.1	
37	5.49	4.89	3.87	2.21	2.10	2.00	2.99	2.17	0.91	0.68	2.52	1.23	1.57	1.68	1.74	0.99	1.5	
31	3.86	4.00	2.15	0.46	0.75	0.10	1.20	1.98	1.61	1.12	1.48	0.64	1.32	1.66	0.62	0.82	1.2	
				[illegible]	[illegible]	0.05	0.59	1.02	1.52	1.63	1.32	0.22	1.00	0.43	0.52	0.69	0.4	

TABLE 7: MECHANICAL ANALYSES OF THE TALCHIR BOULDER BED (CONTINUED)

RAMGARH					COALFIELD							
sal	boulder	bed			Upper	boulder	bed			Basal	boulder	bed
42	43	44	45	46	47	48	49	50	51	52	53	54
7.25	7.13	6.42	6.72	4.82	4.61	4.58	11.65	12.65	3.49	1.33	1.59	2.73
9.10	8.87	7.51	9.23	9.12	8.32	9.00	18.79	17.31	3.54	4.70	0.58	3.31
9.98	11.51	10.85	10.45	14.54	12.59	16.66	12.72	14.49	10.85	12.66	5.24	8.89
12.52	12.32	11.48	11.51	15.06	14.18	16.81	9.43	10.32	15.88	16.81	17.01	15.24
14.89	16.29	15.73	15.75	19.75	18.74	19.22	10.76	10.39	19.51	20.26	22.22	21.97
4.29	4.83	7.23	4.34	10.94	11.99	10.26	6.97	5.83	9.24	9.16	10.22	8.41
16.63	19.52	18.12	14.96	12.32	16.09	12.76	14.89	19.35	13.07	12.27	13.76	14.27
5.91	5.09	6.18	6.25	4.33	5.41	3.68	4.05	4.19	5.71	5.60	5.29	5.99
4.73	6.27	5.23	4.27	3.20	2.59	2.87	3.78	1.92	6.21	6.00	5.49	5.25
4.25	5.45	3.68	3.51	2.12	1.21	1.16	2.79	0.86	5.57	5.57	5.30	6.43
4.01	3.82	3.52	4.21	1.15	1.43	1.00	1.34	0.80	4.41	2.75	5.26	4.29
3.75	2.75	2.41	2.16	0.96	0.85	0.98	1.31	0.76	1.29	2.18	4.83	2.82
			[illegible]	0.82	1.00	0.62	1.30	0.70	1.23	0.71	3.21	0.40

TABLE 7: MECHANICAL ANALYSES OF THE TALCHIR BOULDER BED (CONTINUED)

	JHARIA						COALFIELD										
	boulder bed			Basal boulder			bed		Basal	boulder	bed			Cross-bedded			horiz
	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74
8	12.22	12.92	10.89	0.81	1.45	0.80	1.23	1.02	0.46	0.81	0.62	0.92	0.00	18.99	17.02	16.82	16.29
3	12.41	13.00	12.75	2.19	1.48	1.65	1.47	1.81	1.23	0.99	1.01	1.23	0.71	23.29	25.52	26.79	24.85
4	10.27	9.27	11.23	8.38	6.90	7.72	7.84	8.33	5.74	5.41	5.99	4.98	4.23	18.19	16.23	16.11	15.79
9	12.25	11.57	13.72	15.69	15.18	16.16	17.01	16.47	13.45	14.25	14.23	14.75	15.16	14.09	14.15	13.23	15.01
3	14.02	15.65	16.44	20.21	19.24	21.11	20.22	21.24	21.88	22.13	22.00	21.56	20.38	12.79	12.74	12.01	13.23
5	6.97	7.60	6.49	10.25	9.40	10.96	9.83	9.66	11.96	11.23	11.82	9.36	10.07	5.84	4.59	6.79	4.73
3	12.88	13.22	11.57	15.29	14.06	14.98	15.79	16.27	18.73	18.04	18.41	19.66	18.98	2.03	3.75	2.75	3.63
7	4.87	3.97	5.32	6.18	6.54	2.78	5.45	4.95	6.62	7.06	6.78	7.21	8.01	1.51	1.69	1.56	0.82
1	4.01	3.52	4.93	6.72	7.74	9.13	7.21	8.63	5.98	6.22	6.45	5.82	5.92	0.92	1.21	1.00	0.76
0	3.03	2.85	2.15	5.01	6.78	4.90	5.94	4.99	4.06	4.31	4.20	3.51	4.41	0.80	0.84	0.98	0.57
6	1.52	2.52	1.97	2.91	3.57	3.18	2.98	3.12	4.26	4.76	3.89	5.53	5.79	0.71	0.80	0.65	1.00
3	1.93	2.17	1.02	2.07	2.86	2.35	2.01	1.79	2.00	2.25	3.00	3.75	4.25	0.59	0.72	0.43	0.98
4	2.66	1.74	1.52	4.29	4.80	4.28	2.52	1.22	2.98	2.02	1.40	1.75	2.09	0.29	0.72	1.88	2.34

TABLE 7: MECHANICAL ANALYSES OF THE TALCHIR BOULDER BED (CONTINUED)

CLASS (mm.)	RANIGANJ		COALFIELD		
	Basal		boulder		bed
	76	77	78	79	80
4-2	1.09	0.92	0.55	2.57	1.84
2-1	2.52	1.57	1.89	3.94	1.95
1-1/2	6.67	4.94	5.43	5.72	4.54
1/2-1/4	16.95	13.31	14.87	15.26	14.36
1/4-1/8	20.12	22.76	20.99	22.65	21.57
1/8-1/16	10.67	12.23	10.55	9.98	12.36
1/16-1/32	15.64	17.81	16.53	16.69	14.32
1/32-1/64	3.78	6.05	4.92	4.51	5.78
1/64-1/128	6.43	6.54	5.53	7.22	7.29
1/128-1/256	4.84	5.18	6.74	3.85	3.68
1/256-1/512	4.01	4.03	4.13	3.49	4.58
1/512-1/1024	3.98	2.72	3.82	2.53	4.74
1/1024-1/2048	3.30	1.94	2.05	1.56	2.69

Each pipette sample is transferred to a weighed 50 cc. beaker and evaporated to dryness at a constant temperature of 100°C. in an electrically controlled thermostat and the weight of the sediment in each beaker is then computed after making a correction for the weight of dissolved sodium oxalate. The volume of the pipette sample being 1/50th of the total suspension (1000 cc.), the weight of the sediment is multiplied by 50 so as to convert it in terms of the original weight and then the amount of sediment in each grade is computed by subtracting the successive weights so obtained. From these values the weight percentage in each grade is calculated.

As the pipette method takes considerable time, the modification suggested by Rittenhouse (1933, p. 44) was applied. The time table for the drawing of samples was so arranged that the process of shaking the suspension in between sampling was reduced to a minimum and in this way it was possible to run a battery of 5 analyses simultaneously.

Statistical treatment of the data

The results of the mechanical analyses of the fine fraction in the various coalfields appear in Table 7 for ready comparison. Of the 80 samples analysed, 40 come from the basal boulder bed, and 20 each from the upper boulder bed and its cross-bedded horizons. As mentioned earlier, five compound samples from each locality were analysed and as the results of the analyses show a great uniformity in mechanical composition at a given locality, the average of 5 analyses was determined for the purpose of graphical representation of the mechanical composition of this fraction. The average analyses appear in Table 8 in which each vertical column bears a number - the numerator showing the serial number of the average analysis, while the denominator showing the sample numbers for which the average stands. For example, the number $\frac{5}{21-25}$ indicates that the serial number of the average analysis is 5 and that the analysis listed in the column represents the average of sample numbers 21 to 25.

Histograms showing the size frequency distribution of the fine fraction of the basal boulder bed from the various coalfields of the Damodar Valley constructed from the data given in Table 8, appear in Fig. 4. Diagrams a-h show much resemblance to one another in their general appearance, specially in respect to their sorting, the polymodal nature of the frequency distribution and the amount of material in the modal class. In all diagrams, the material is spread over 13 Wentworth grades and shows a polymodal size frequency distribution indicating thereby that the material is very poorly sorted. The chief ingredient in diagrams a-d lies in the 1/16-1/32 mm. class (very coarse silt), while the next most prominent mode lies in the 1/4-1/8 mm. class (fine sand). In diagrams e-h the chief ingredient falls in the 1/4-1/8 mm. class and the secondary mode lies in the 1/16-1/32 mm. class. Thus the position of the modal class and the secondary mode is interchanged between the two sets of histograms. Further, the fine admixture in diagrams a-d equals the coarse admixture, but in diagrams e-h the fine admixture greatly exceeds the coarse and the frequency distribution is skewed to the right, that is, towards the finer fractions. The amount of material in the modal class, irrespective of its position, is always small and ranges from 17.94% by weight in diagram c to 23.25% in diagram a.

Figure 5, diagrams a-d, shows the size frequency distribution of the fine fraction of the upper boulder bed, while diagrams e-h show the same characteristic of the cross-bedded horizons. Here also a close resemblance in general appearance between diagrams a-d on the one hand and e-h on the other, is apparent. The material in the upper boulder bed is spread over 12 to 13 Wentworth grades and shows a polymodal size distribution and in this respect it does not differ from the basal boulder bed. Table 9, however, shows that 90.86% to 96.05% of the material by weight in this horizon falls in 9 Wentworth grades, while 83.61% of the material by weight in the basal bed falls in the same range. In contrast to this, 84.01% to 91.52% of the material in the cross-bedded horizons falls in only 6 grades.

The chief ingredient in histograms of the upper boulder bed lies generally in 1/4-1/8 mm. class (fine sand), but in Fig. 5, diagram b, it lies in 1-1/2 mm. class (coarse sand). In the cross-bedded horizons the chief ingredient occupies the 2-1 mm. class (very coarse sand) except in diagram e in which the modal class falls in 1/2-1/4 mm. class (medium sand). In all cases, the fine admixture greatly exceeds the coarse and the size frequency distributions are skewed to the right, but the skewness is much less prominent in the upper boulder bed as compared to the cross-bedded horizons. The amount of material in the modal class in the upper boulder bed ranges from 14.97% by weight in diagram d to 16.06% in diagram a, in the cross-bedded horizons it varies from 22.81% in diagram e to 25.91% in diagram f.

CLASS (mm.)
4-2
2-1
1-1/2
1/2-1/4
1/4-1/8
1/8-1/16
1/16-1/32
1/32-1/64
1/64-1/128
1/128-1/256
1/256-1/512
1/512-1/1024
1/1024-1/2048

Inasmuch as histograms represent a discrete frequency distribution and also because their shapes are affected by the choice of the class limits, a clearer and a more precise idea of the size frequency distribution can be obtained by drawing cumulative frequency curves which not only represent a continuous distribution but also yield directly several valuable statistical parameters. The cumulative frequency curves representing 16 average analyses, appear in Fig. 6 and were constructed by plotting the total weight percentage larger than the limiting dimensions (coarser) listed in Table 9 against the diameters of each fraction in PHI units (Krumbein 1934, pp. 65-77). Krumbein's PHI scale is of great value in the analysis of sedimentary data and has been used in this investigation in preference to the geometric millimeter scale. This is so far the reason that logrithmic graph paper is not required for plotting the data and the readings obtained from the Wentworth scale can be plotted directly on ordinary arithmetic graph paper. Also, the curves obtained are more symmetrical and some of the statistical constants obtained on this scale are more easily visualised. If, however, the millimeter equivalents of the PHI values are needed for substituting in formulae or for easier comprehension of the values, reference can be made to conversion charts (Krumbein, 1936; Truesdell and Varnes, 1950; Inman 1952), or to an excellent conversion table published recently by Page (1955, pp. 286-291).

The relationship between the Wentworth grade limits and the PHI scale is as follows:-

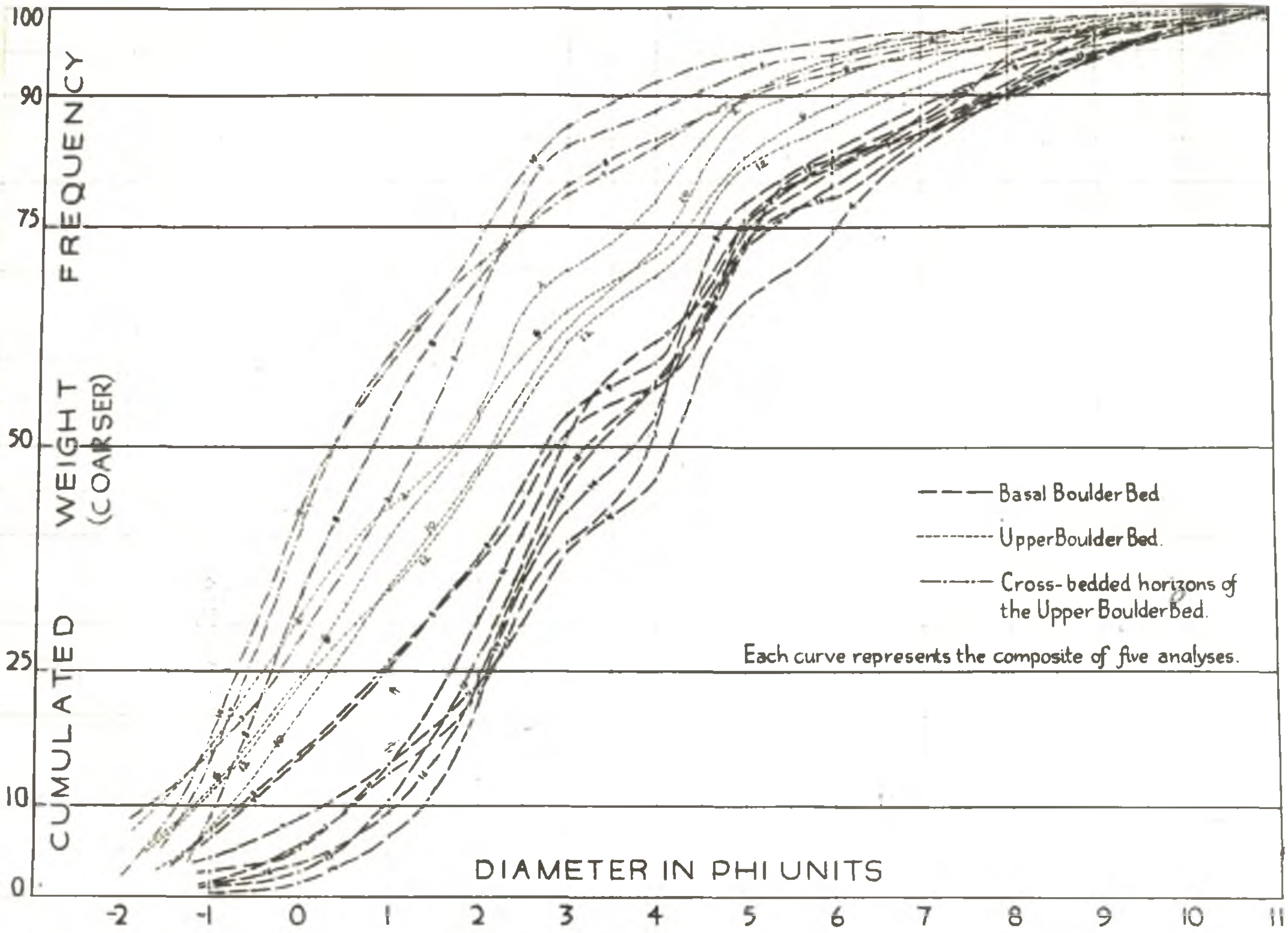


FIG. 6. Cumulative curves showing mechanical composition of the matrix of the Talchir boulder beds in the Damodar Valley Coalfields.

Diameter in mm.	PHI Scale	Diameter in mm.	PHI Scale
4	-2	1/32	5
2	-1	1/64	6
1	0	1/128	7
1/2	1	1/256	8
1/4	2	1/512	9
1/8	3	1/1024	10
1/16	4	1/2048	11

The cumulative frequency curves appearing in Fig. 6, have been numbered 1 to 16 - each number representing the serial number of the average analysis in Table 8. The curves fall broadly into three groups which can be distinguished in the central part of the figure - group I contains curves, 1, 4, 5, 9, 11, 13, 14, & 16 which show the mechanical composition of the basal boulder bed, while groups II and III consist of curves 2, 6, 10, 12 and 3, 7, 8, 15 respectively, the former representing the composition of the upper boulder bed and the latter that of the cross-bedded horizons. The differentiation between the cumulative curves of group I and those of groups II and III is very clear as nowhere do the curves of the former, which constitute a broad band in the upper and middle parts of the figure, overlap those of the other two. The curves 5 & 9 deviate from the general trend

TABLE 10: STATISTICAL CONSTANTS OF THE SIZE FREQUENCY DISTRIBUTION (CONTINUED)

OALFIELD	Median		Q_3		Q_1		P_{90}		P_{10}		Deviation		Skewness
	ø	mm	ø	mm	ø	mm	ø	mm	ø	mm	So	QDø	
UPPER BOULDER BED													
orth Karanpura $(\frac{2}{6-10})$	1.75	0.2973	3.70	0.0769	-0.45	1.3660	5.00	0.0313	-1.60	3.0314	4.21	2.07	-0.125
ast Bokaro $(\frac{6}{26-30})$	1.80	0.2872	4.35	0.0490	0.05	0.9659	6.30	0.0127	-1.20	2.2974	4.44	2.15	+0.400
amgarh $(\frac{10}{46-50})$	2.15	0.2253	4.20	0.0544	0.35	0.7846	5.55	0.0213	-0.80	1.7411	3.82	1.92	+0.125
haria $(\frac{12}{56-60})$	2.20	0.2176	4.50	0.0442	0.10	0.9330	6.75	0.0093	-1.15	2.2191	4.60	2.20	+0.100
CROSS-BEDDED HORIZONS													
orth Karanpura $(\frac{3}{11-15})$	1.30	0.4061	2.35	0.1961	-0.25	1.1892	4.40	0.0625	-1.70	3.2490	2.46	1.30	-0.250
ast Bokaro $(\frac{7}{31-35})$	0.35	0.7846	2.50	0.1768	-0.60	1.5157	4.95	0.0324	-1.25	2.3784	2.92	1.55	+0.600
ast Bokaro $(\frac{8}{36-40})$	0.80	0.5743	2.50	0.1768	-0.35	1.2746	5.10	0.0292	-0.95	1.9319	2.68	1.42	+0.325
haria $(\frac{15}{\ldots})$	0.35	0.7846	2.10	0.2333	-0.70	1.6245	3.65	0.0797	-1.40	2.6390	2.64	1.40	+0.3[illegible]

COALFIELD	BASAL BOULDER BED: Median		Q_3		Q_1		P_{90}		P_{10}		Deviation		Skewness
	ø	mm	ø	mm	ø	mm	ø	mm	ø	mm	So	QDø	
North Karanpura $(\frac{1}{1-5})$	3.95	0.0647	4.95	0.0324	2.15	0.2253	7.50	0.0055	0.60	0.6598	2.65	1.40	-0.400
South Karanpura $(\frac{4}{16-20})$	4.15	0.0563	6.05	0.0151	2.10	0.2333	7.95	0.0040	0.25	0.8409	3.94	1.97	-0.075
West Bokaro $(\frac{5}{21-25})$	2.85	0.1387	5.05	0.0302	0.90	0.5359	7.75	0.0047	-0.70	1.6245	4.21	2.07	-0.125
Ramgarh $(\frac{9}{41-45})$	2.75	0.1487	4.75	0.0372	0.95	0.5176	7.30	0.0064	-0.60	1.5157	3.74	1.90	+0.100
Ramgarh $(\frac{11}{51-55})$	2.95	0.1294	4.95	0.0324	1.70	0.3078	7.45	0.0057	0.55	0.6830	3.10	1.63	+0.375
Jharia $(\frac{13}{61-65})$	3.20	0.1088	5.15	0.0282	1.90	0.2679	7.85	0.0043	0.95	0.5176	3.10	1.63	+0.325
Jharia $(\frac{14}{66-70})$	3.75	0.0743	5.30	0.0254	2.10	0.2333	8.05	0.0038	1.40	0.3789	3.05	1.60	-0.050
Raniganj $(\frac{16}{76-80})$	3.30	0.1015	5.20	0.0272	2.00	0.2500	7.95	0.0040	1.05	0.4841	3.05	1.60	+0.300

in the lower part of the figure and merge with those of the other two groups just above the 5% line. Curves of groups II and III, although forming distinct bands in the upper central part of the figure, overlap each other at both the fine and coarse ends of the distribution.

The conventional statistical constants, namely the median (Md), the first (Q1) and the third (Q3) quartiles and the ninetieth (P 90) and the tenth (P 10) percentiles were directly read in terms of the PHI units from the curves by reading PHI diameters corresponding to frequencies of 50, 25, 75, 90 and 10%. Their millimeter equivalents were determined with the help of the conversion table mentioned earlier (Page, loc. cit.). The statistical constants and the quartiles measures calculated from them appear in Table 10.

The median diameter, as defined by Krumbein and Pettijohn (1938, p. 229), is the "middlemost member of the distribution; it is that diameter which is larger than 50 per cent of the diameters in the distribution and smaller than the other 50 per cent". Its value in terms of PHI units can be readily determined from the cumulative frequency curve by reading the diameter value on the PHI scale corresponding to the point where the 50 per cent line cuts the curve. The median values of samples from the various horizons of the boulder bed, appearing in Table 10, differ materially from one another. Those of the basal boulder bed range from 2.75Ø to 4.15Ø (0.14 mm. to 0.0563 mm.), while the variation in the upper boulder bed is from 1.75Ø to 2.20Ø (0.2973 mm. to 0.2176 mm.) and that in the cross-bedded horizons from 0.35Ø to 1.30Ø (0.7846 mm. to 0.4061 mm.). As the range of median values in any one horizon does not overlap that of the others and as the values are significantly different from one another, it may be concluded that the fine fractions of the three horizons can be differentiated on the basis of their median diameter values. The fine fraction of the basal boulder bed on an average is finer grained as compared to the upper one; and that of the cross-bedded horizons is the coarsest.

Another important statistic of the size frequency distribution of a sediment is its average spread about the median. Although several types of deviation measures are available for the determination of this characteristic, only the geometric and the PHI quartile deviations have been calculated in the present work. The geometric quartile measure - the sorting coefficient of Trask (1932) - is given by the formula $So=(Q1/Q3)^{\frac{1}{2}}$ and, being a ratio, has the advantage of eliminating the size factor and also the units of measurement. It is, therefore, superior to the equivalent arithmetic measure. According to Trask (loc. cit.) a sorting coefficient value of 2.5 or less indicates a well sorted sediment, a value of about 3 shows normal sorting while values larger than 4.5 indicate poor sorting.

The PHI quartile deviation, which is also a measure of the spread of the frequency distribution, is given by the formula $QD\phi = 1/2(Q3\phi - Q1\phi)$ and represents half the spread between the two quartiles directly in terms of the number of Wentworth grades involved. For example, a $QD\phi$ value of 4.44 indicates that 8.38 Wentworth grades lie between the first and the third quartiles. It is for this reason that the PHI quartile deviation values, in contrast to the equivalent geometric values, can be directly used for comparing the relative spread of different samples.

The So and QDØ values for the average analyses are listed in Table 10. The So values for the basal boulder bed, which range from 2.65 to 4.21, show that the fine fraction in this horizon is moderately to almost poorly sorted. For the upper boulder bed these values range from 3.82 to 4.60 indicating that this fraction is, on an average, more poorly sorted as compared to the former. The same conclusion is reached when the QDØ values are examined and since the PHI quartile deviation is a logrithm, a direct comparison between these values from the two horizons can be made. As a result it is seen that, on an average, the upper boulder bed is about 1½ times more poorly sorted as compared to the basal bed. The cross-bedded horizons of the upper boulder bed show a range of So values from 2.46 to 2.92 indicating that the fine fraction in these units is well to normally sorted. A comparison of QDØ values shows that the upper boulder bed is roughly 1½ times more poorly sorted as compared to the cross-bedded horizons.

The differences in the textural composition between the various horizons of the boulder bed are brought out more clearly when the per cent composition of each sample in terms of the sand, silt and clay proportions (Table 11) is plotted on a triangular diagram as in Fig. 7.

The points representing the 80 samples fully analysed fall clearly into three groups. The lowest group of points (lowest sand content) in

TABLE 11: PERCENTAGE COMPOSITION OF TALCHIR BOULDER BED

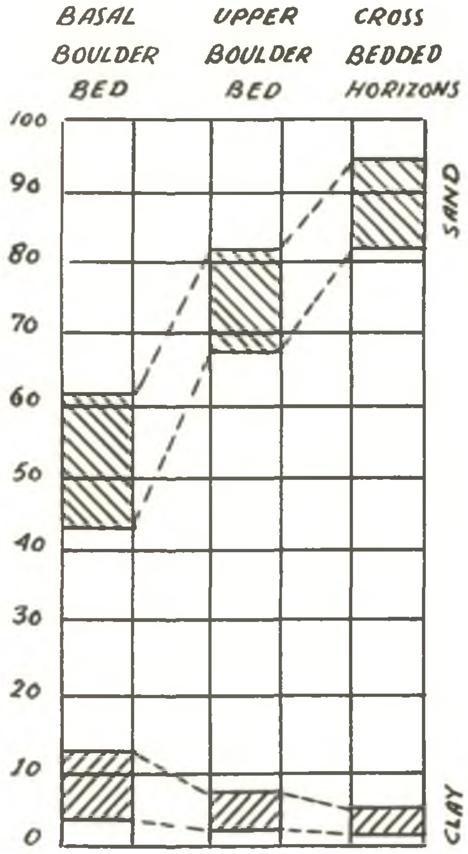
S. NO.	SAND %	SILT %	CLAY %	S. NO.	SAND %	SILT %	CLAY %
1.	48.38	47.69	3.93	15.	89.24	8.82	1.94
2.	47.72	46.40	5.88	16.	51.10	40.13	8.77
3.	52.70	40.07	7.23	17.	43.06	45.12	11.82
4.	57.01	35.99	7.00	18.	44.05	46.95	9.00
5.	53.39	42.09	4.52	19.	47.21	42.82	9.97
6.	74.99	22.36	2.65	20.	46.54	43.91	9.55
7.	75.65	21.33	3.02	21.	59.73	35.26	5.01
8.	79.11	18.43	2.46	22.	56.96	34.52	8.52
9.	80.72	17.18	2.10	23.	53.24	36.75	10.01
10.	78.58	19.30	2.12	24.	56.65	32.41	10.94
11.	84.72	10.69	4.59	25.	57.02	36.05	6.93
12.	87.49	9.99	2.52	26.	70.09	26.92	2.99
13.	86.85	10.14	3.01	27.	74.02	23.13	2.85
14.	87.15	10.66	2.19	28.	72.84	25.01	2.15

TABLE 11: PERCENTAGE COMPOSITION OF TALCHIR BOULDER BED (CONTINUED)

S. NO.	SAND %	SILT %	CLAY %	S. NO.	SAND %	SILT %	CLAY %
29.	72.49	22.73	4.78	43.	60.95	36.33	7.72
30.	70.32	24.51	5.17	44.	59.27	33.21	7.52
31.	81.94	14.02	4.04	45.	58.50	33.99	7.51
32.	83.74	12.73	3.53	46.	74.23	21.98	3.79
33.	84.62	13.29	2.09	47.	70.43	24.30	5.27
34.	82.12	12.56	5.32	48.	76.53	20.47	3.10
35.	83.68	12.43	3.89	49.	70.32	25.51	4.17
36.	82.34	13.89	3.77	50.	70.97	26.32	2.71
37.	91.04	6.08	2.88	51.	62.51	30.56	6.93
38.	85.92	11.58	2.50	52.	64.92	29.44	5.64
39.	88.47	8.26	3.27	53.	56.86	29.84	13.30
40.	84.99	12.49	2.52	54.	60.55	31.94	7.51
41.	60.30	30.52	9.18	55.	54.99	36.74	8.27
42.	58.03	31.51	10.45	56.	68.92	24.41	6.67

TABLE 11: PERCENTAGE COMPOSITION OF TALCHIR BOULDER BED (CONTINUED)

S. NO	SAND %	SILT %	CLAY %	S. NO.	SAND %	SILT %	CLAY %
57.	67.52	25.31	7.17	69.	52.79	36.20	11.01
58.	68.13	24.78	7.09	70.	50.55	37.32	12.13
59.	70.01	23.56	6.43	71.	93.19	5.26	1.55
60.	71.52	23.97	4.51	72.	90.25	7.49	2.26
61.	57.53	33.20	9.27	73.	91.75	6.29	1.96
62.	53.65	35.12	11.23	74.	89.90	5.78	4.32
63.	58.40	31.79	9.81	75.	92.20	5.94	1.86
64.	58.10	34.39	7.51	76.	58.02	30.69	11.29
65.	59.03	34.84	6.13	77.	55.73	35.58	8.69
66.	54.82	35.63	9.55	78.	54.28	35.72	10.00
67.	54.81	35.39	9.80	79.	60.15	32.27	7.58
68.	55.67	35.84	8.49	80.	56.92	31.07	12.01



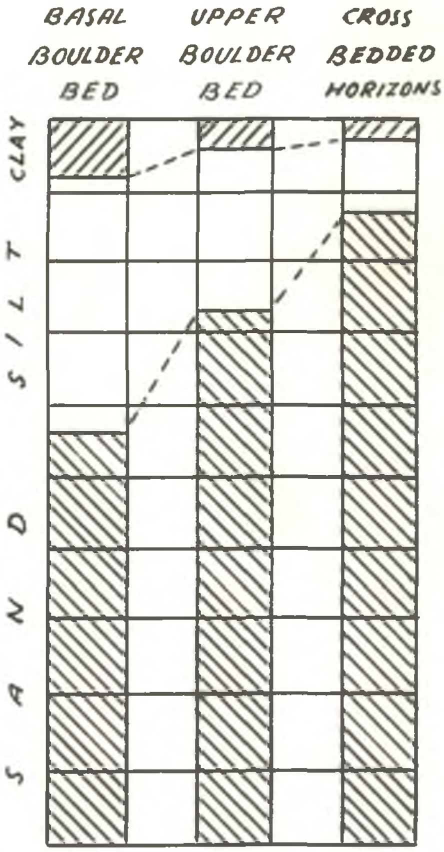
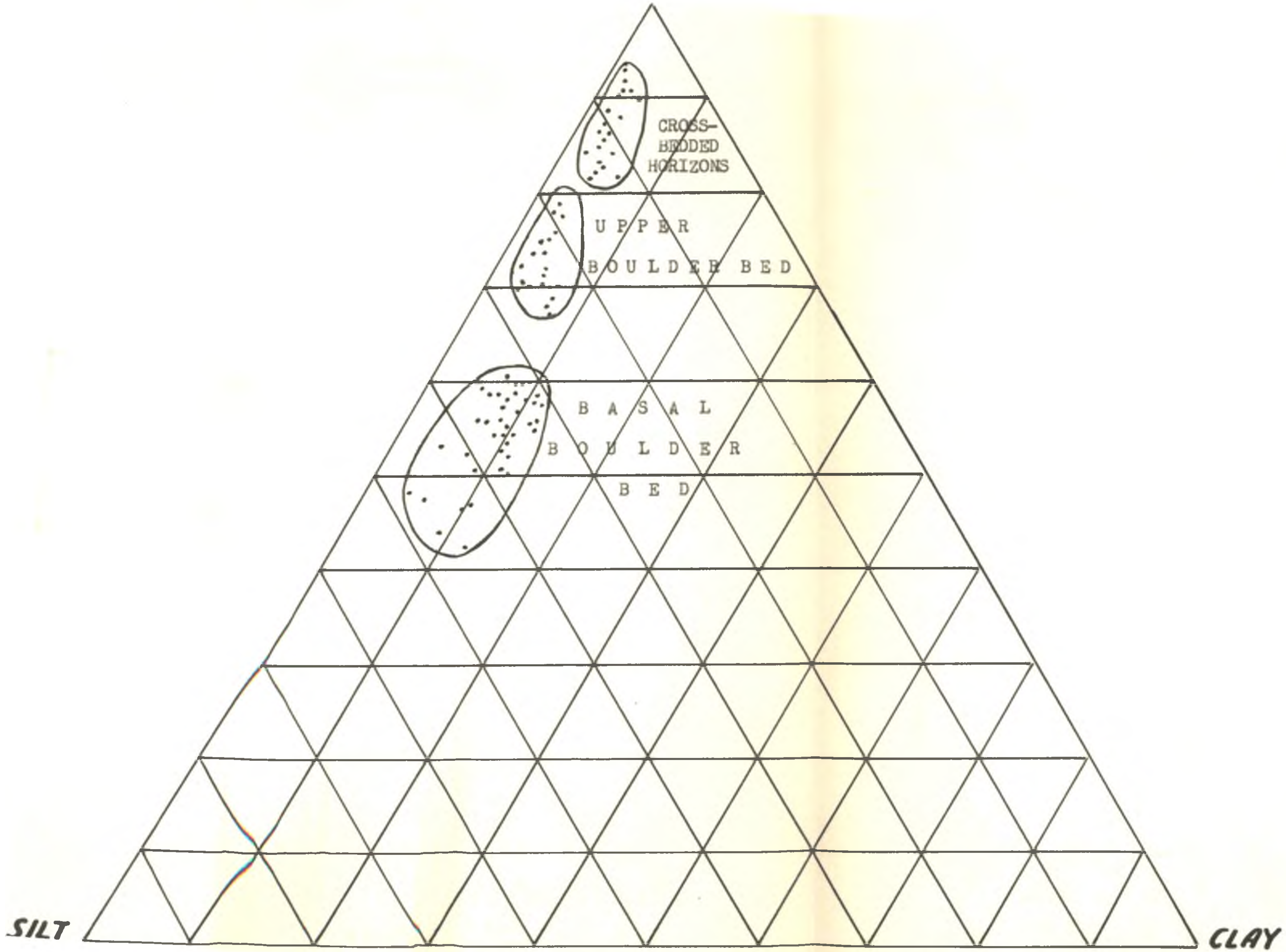


FIG. 8. RANGE OF SAND AND CLAY PERCENTAGES IN THE TALCHIR BOULDER BEDS.

FIG. 9. AVERAGE PERCENTAGE OF SAND AND CLAY IN THE TALCHIR BOULDER BEDS.



... OF THE FINE FRACTION OF THE TALCHIR BOULDER BEDS IN TERMS OF SAND, SILT the diagram represents the mechanical composition of the basal boulder bed, the middle one that of the upper boulder bed and the upper most group (highest sand content) shows samples from the cross-bedded horizons. In no case does the boundary of one group overlap that of the other, but those of the upper boulder bed and the cross-bedded horizons are very close to each other. The proximity of the two boundaries has a genetic significance in view of the fact that the cross-bedded horizons represent the reworked portions of the upper boulder bed.

Fig. 7 clearly shows that the differentiation between the three horizons of the boulder bed on the basis of the per cent composition of the samples is entirely valid, thus confirming the findings of Krumbein (1933, p. 404), Shepps (1953, p. 41) and Dreimanis and Reavely (1953, p. 245).

The range in percentage of sand and clay in samples of the various horizons of the boulder bed appears in Table 12 and is represented graphically in Fig. 8.

TABLE 12: RANGE IN PERCENTAGE OF SAND AND CLAY

Horizon	Sand	Clay
Basal boulder bed	43.06 - 60.95	3.93 - 12.13 (based on 40 samples)
Upper boulder bed	67.52 - 80.72	2.10 - 7.17 (based on 20 samples)
Cross-bedded horizons	81.94 - 93.19	1.55 - 5.32 (based on 20 samples)

Considering the large area covered by the samples and the relatively small variation in the sand and clay percentages, it is apparent that the various horizons of the boulder bed are texturally quite homogeneous throughout the Damodar Valley Coalfields. Further, it is clear from the above data that there is no overlapping in the percentage of sand variation between the basal and the upper boulder beds and the two can be differentiated from each other on the basis of their sand percentage. The difference between the upper boulder bed and the cross-bedded horizons is not sharp in this respect and a transition may be found if more analyses were run.

The average mechanical composition of the boulder bed in terms of the sand, silt and clay percentages is given in Table 13 and is also shown graphically in Fig. 9. The data is self explanatory.

TABLE 13: AVERAGE MECHANICAL COMPOSITION (PER CENT)

Horizon	Sand	Silt	Clay
Basal boulder bed	55.68	36.14	8.18
Upper boulder bed	72.76	23.20	4.04
Cross-bedded horizons	87.19	9.96	2.85

MICROPETROLOGY

Basal boulder bed

In the hand specimen the fine fraction of the basal boulder bed is green to blackish green in colour and is compact when fresh but crumbles on weathered surfaces. This fraction is very poorly sorted and consists of angular particles of all sizes and of different composition scattered in a fine structureless matrix. It appears uniform both vertically and horizontally as regards its colour, texture and composition throughout the Damodar Valley Coalfields.

In thin sections, this fraction shows a remarkable textural uniformity. Plate 4, Figs. 1-4 and plate 5, Figs. 1 and 2 illustrate this feature and show the general nature of the rock in the various coalfields under low magnification. The most characteristic feature of this fraction is the presence of abundant dark, clayey, paste-like detrital matrix in which are scattered particles of various sizes and different composition. The coarse detrital fragments which constitute the framework of the rock, show practically no points of contact and the intervening space is filled up with the matrix. The framework of the rock is therefore disrupted. It is important to note, however, that the distinction between the framework and the matrix is arbitrary and that fragments smaller than about 20 microns have been included in the latter (Williams and others, 1953, p. 297 footnote).

Another important textural feature of this fraction is the enormous variation in size of the detrital constituents. Particles of all sizes from large fragments to clay-sized grains lie mixed up together, but no particular size appears to be dominant. As is clearly seen in the figures mentioned above, the absolute difference in size of the particles is more than 100 times showing thereby that the sorting of this fraction is very poor.

The high degree of angularity of the majority of detrital grains is also a noteworthy feature. All the grains, however, are not equally angular and the degree of roundness attained by a given particle is determined by its physical characters. Quartz grains are invariably angular but rock fragments, like shale and slate, are rounded to well rounded. This is seen in Plate 4, Fig. 2 in the upper left-hand corner and in Plate 4, Fig. 3 in the lower centre. A fragment of coarse grained quarzite in the central portion of Plate 4, Fig. 2 is sharply angular. In general the fine grained, soft rock fragments show a better rounding of their edges as compared to the coarse grained ones. Felspar grains are often rounded to sub-rounded as in the left-hand centre of Plate 5, Fig. 2, but angular grains also occur occasionally as in the left-hand top corner of Plate 4, Fig. 4.

The composition of the fine fraction of the basal boulder bed is complex and varied types of components differing in their mineralogy and texture constitute the bulk of the rock. Inspite of its heterogeneous composition, this fraction is remarkably uniform in character throughout

TABLE 14: MODAL COMPOSITION OF THE FINE FRACTION OF THE BASAL BOULDER BED (PER CENT)

Coalfield	Quartz	Felspars	Rock fragments	Micas	Minor accessories	Matrix
North Karanpura	20.75	11.11	7.65	1.23	1.33	57.93
	20.30	8.70	5.26	1.36	1.49	62.89
	22.67	10.97	6.33	1.37	1.90	56.76
	29.92	8.64	7.49	0.12	2.01	57.82
South Karanpura	25.27	6.52	10.29	0.28	0.16	57.48
	30.16	7.24	11.98	0.00	0.62	50.00
	24.27	7.48	11.80	0.62	0.64	55.19
	27.28	12.33	8.92	0.00	1.88	49.59
West Bokaro	29.07	12.66	12.60	0.00	0.09	45.58
	29.19	10.48	10.40	0.00	0.63	49.30
	28.62	9.75	12.40	0.00	0.72	48.51
	25.36	10.23	6.99	0.42	2.12	54.88

TABLE 14: MODAL COMPOSITION OF THE FINE FRACTION OF THE BASAL BOULDER BED (CONTINUED) (PER CENT)

Coalfield	Quartz	Felspars	Rock fragments	Micas	Minor accessories	Matrix
Ramgarh	32.09	8.24	9.73	0.00	0.73	49.21
	31.62	9.91	9.27	0.00	0.68	50.52
	30.32	5.27	8.10	0.00	0.55	55.76
	26.55	13.88	7.56	0.00	3.11	48.90
Jharia	26.33	12.01	10.76	1.10	2.17	47.63
	28.44	13.62	7.58	0.00	2.91	47.45
	30.20	11.78	8.27	0.75	2.01	46.99
	30.32	12.33	9.65	0.00	1.88	45.82
Raniganj	32.14	11.92	7.40	0.00	2.17	46.37
	33.87	6.50	7.56	0.00	2.93	49.14
	30.28	9.15	7.22	0.00	1.98	51.37
	32.31	10.75	8.11	0.00	1.98	46.85

the Damodar Valley Coalfields. Table 14, shows the modal composition of this fraction from the different localities.

Quartz is the most dominant constituent of the framework and its amount varies from 20.30% to 33.87% . The grains are generally clear but quite a few are turbid containing various types of inclusions. The large quartz grain in Plate 7, Fig. 2 shows a cluster of dusty and accicular inclusions while the large grain in the central part of Plate 7, Fig. 3 shows small tourmaline and rutile inclusions along with numerous unidentifiable dusty particles. It is interesting to note that generally the equant grains of quartz show sharp extinction while the elongate particles show undulatory extinction. Quartz grains of igneous and metamorphic derivation are present in the rock, but it is not easy to ascertain their relative proportions.

The amount of felspars in this fraction varies from 5.27% to 13.88%. Microcline is the most common variety present constituting as much as 85% of the total felspars and occurs in altered rounded to angular grains as seen near the left-hand edge in Plate 5, Fig. 2. Orthoclase grains show a high degree of alteration and often cannot be distinguished from the matrix into which they gradually merge. One such altered grain, seen in the left-hand top corner in Plate 6, Fig. 2, clearly demonstrates this fact. Completely altered grains, therefore, may well have contributed to the formation of the matrix. Plagioclase is also slightly altered and occurs in subhedral angular grains.

Rock fragments are present in nearly the same amount as the felspars, their percentage varying from 5.26% to 12.60%. These fragments are of varied nature and may be broadly classified into two groups. The first includes coarse grained rock fragments of granite, gneiss, coarse quartzite, and mica-, hornblende-, actinolite- and epidote-schists. These fragments are generally large and angular and occur in small quantity in the fine fraction. The second group consists of fine grained rock fragments like shale, slate, fine quartzite, greenstone and quartz-sericite schist.

Sometimes the rock fragments have distinct outlines and occur as undistorted particles. This feature is seen in the left-hand top corner of Plate 4, Fig. 2, in lower centre of Plate 4, Fig. 3 and in the upper central part of Plate 5, Fig. 3. The large fragment of mica-schist in Plate 5, Fig. 4 is spindle-shaped. Its thin end appears drawn out, while the truncated blunt end is squeezed in between the quartz grains. In the lower central part of the figure the rock fragment appears to bend round a quartz grain. These features clearly show that the soft rock fragments have a tendency to flow in between the more resistant components of the framework.

The above feature is seen more clearly in Plate 6, Figs. 1 and 2. In the right-hand part of Fig. 1 a large sericitic shale fragment placed edgewise shows that it has flowed and filled up the irregular empty spaces between the quartz grains. Two other smaller fragments towards the left show the same feature. Another shaly fragment in the central part of Plate 6, Fig. 2 has likewise flowed and curved round the angular quartz grain.

The boundary outline of the rock fragments in these cases is either distinct as in Plate 5, Fig. 4 or hardly distinguishable from the matrix as in Plate 6, Figs. 1 and 2. In Plate 6, Fig. 3 a shaly fragment in the central part shows no distinct outline. It is important to note that the texture and composition of the shale fragment is identical with that of the matrix and that the fragment merges into the matrix. Plate 6, Fig. 4 also shows essentially the same feature, but in this case the nature of the matrix is exactly identical with that of the shaly fragment which occupies the middle and the upper parts of the figure. The boundary of the rock fragment which is very indistinct passes a little distance below the central part of the figure. These features prove that a greater part of the matrix of the rock, which is similar in texture and composition to the soft rock fragments, has been derived as a result of crushing of the latter.

Muscovite and biotite are present in a very small quantity and their amount varies from nothing in several specimens to 1.37%. Muscovite is more common and usually occurs as conspicuous laths with distinct outlines but occasionally a cluster of flakes may be present as in Plate 7, Fig. 1. The mica flakes are invariably bent and exhibit frayed ends into which the paste-like matrix has penetrated along the cleavage planes so much so that often the flakes are physically disrupted. The above characteristics show that the flakes are of detrital origin and not a product of reorganisation of the clayey matrix. Biotite occurs sometimes in distinct grains but more commonly in indistinct brownish, non-pleochroic patches and constitutes a very insignificant part of the rock.

Minor accessories constitute between 0.09% and 3.11% of the rock by volume and consist of a large number of minerals, the important ones being garnet, epidotes, zircon, tourmaline, rutile, staurolite and opaque minerals. The accessories have diameters less than 0.30 mm. and vary considerably with respect to roundness. These will be described at length under 'Heavy Minerals' in the following pages.

The dark green matrix is the most characteristic feature of the fine fraction of the basal boulder bed, as it occurs abundantly in all the specimens. Its amount varies from 45.58% to 62.89% and under crossed nicols it is seen to be micro- or cryptocrystalline. It consists of clay-sized quartz grains, chlorite and sericite and from its close association with the soft, fine grained rock fragments it is clear that its major part has been derived as a result of crushing of the rock fragments.

That the material of the matrix is recrystallised or at least considerably reorganised is clearly shown by the fact that the coarse components of the framework have been marginally replaced by the matrix. This is well seen in Plate 7, Fig. 2 where a large quartz grain has been marginally replaced by the chlorite matrix resulting in a fuzzy and indistinct boundary which shows several inlets of the matrix into the body of the grain. This feature is also seen in the large quartz grain at the centre of Plate 7, Fig. 3 which shows a deep inlet of the matrix so that the corroded boundary of the grain seems to merge with the matrix. Rock fragments have also been replaced in a similar fashion and this is best illustrated in Plate 7, Fig. 4, where a fragment of altered basalt has been replaced by the matrix along its upper border.

The above description clearly shows that the fine fraction of the basal boulder bed is immature both texturally and compositionally. Texturally the rock can be described as a "microbreccia" because of its lack of sorting and the angularity of its grains. Compositionally it is like a graywacke as it contains abundant argillaceous matrix and significant amounts of felspars and rock fragments.

<u>Upper boulder bed</u>

The fine fraction of the upper boulder bed in all the coalfields is brown to buff in colour and is easily distinguishable from that of the basal horizon. It contains abundant silty matrix in which are scattered particles of all sizes and even in the hand specimen it shows very poor sorting. In contrast to the basal horizon, the coarse clastic fragments of this fraction are better rounded. The textural and compositional characters of this rock as seen in the hand specimen, are uniform both vertically and horizontally throughout its occurrence in the Damodar Valley Coalfields.

The general nature of this fraction in thin sections under low magnification is illustrated in Plate 8, Figs. 1 - 4. There is a close similarity in general appearance between these figures and those showing the fine fraction of the basal horizon. But certain important features of this fraction such as the lower matrix content, abundance

TABLE 15: MODAL COMPOSITION OF THE FINE FRACTION OF THE UPPER BOULDER BED (PER CENT)

Coalfield	Quartz	Felspars	Rock fragments	Micas	Minor accessories	Matrix
	25.61	14.68	24.07	1.21	3.23	31.19
North Karanpura	25.65	13.43	24.51	0.56	3.50	32.31
	24.80	14.30	22.26	1.80	4.80	32.04
	28.35	11.27	21.79	0.98	3.99	33.62
	33.59	12.09	22.87	0.44	2.53	30.84
Bokaro	33.38	10.19	23.60	1.30	1.18	30.35
	32.29	12.72	20.86	0.58	1.99	31.56
	31.34	10.26	22.93	1.21	2.01	32.25
	33.32	10.84	20.65	0.49	1.88	32.82
Ramgarh	35.62	10.73	19.98	0.58	1.22	31.87
	33.27	12.25	20.58	0.92	1.52	31.46
	32.80	12.45	19.27	0.51	1.49	33.48
	36.20	10.41	20.00	4.82	0.36	28.21
Jharia	39.16	10.82	20.75	3.09	0.64	25.54
	39.32	10.57	21.25	1.03	0.45	27.38
	37.91	12.67	23.16	2.14	0.78	23.34

of rock fragments and a better rounding of the grains are clearly noticeable. The rock contains a large amount of matrix in which are scattered particles of different composition and various sizes. The constituents of the framework vary enormously in size, resulting in very poor sorting; but in Plate 8, Figs. 3 and 4 particles between 0.05 mm. and 0.25 mm. in size are more dominant and the sorting appears to be better.

The framework constituents of this fraction as a whole are better rounded as compared to the basal boulder bed but the dgree of roundness varies considerably with the nature of the individual components. Quartz particles and coarse grained rock fragments are generally angular to subrounded but felspars and fine grained rock fragments show generally rounded to subrounded outlines.

As regards the composition is concerned, the rock is as heterogeneous and complex as the fine fraction of the basal boulder bed but differs from it in containing more rock fragments and quartz and a much smaller amount of the matrix. Table 15 shows the modal composition of this fraction determined from representative samples from the various coalfields to illustrate this point.

The above table clearly shows that this fraction is extremely uniform with respect to its composition throughout the area covered by the samples. The quartz content of the rock varies from 24.20% to 39.32%, felspars from 10.19% to 14.68%, rock fragments from 19.27% to 24.51%, micas from 0.44% to 4.82%, minor accessories from 0.36% to 4.20% and the matrix from 23.34% to 33.62% in the different coalfields. The variation in the amount of quartz and the minor accessories appears to be roughly systematic - quartz content of the rock increasing from the North Karanpura coalfield in the west to the Jharia coalfield in the east, while the minor accessories show an opposite trend. The other components do not show any regular variation.

Quartz is by far the most abundant constituent of the framework and shows a wide range of particle size. Most of the grains are clear and show sharp extinction, but a few are often strained and show dusty inclusions which may be arranged in rows or may occur in patches. This is seen in the big grain in Plate 9, Fig. 4.

All the varieties of felspar occurring in the fine fraction of the basal boulder bed also occur in this fraction in approximately the same proportion. Microcline is much altered and occurs in rounded grains but plagioclase is generally clear and occurs in subhedral grains. Orthoclase is rarely present and is so much altered that it merges imperceptibly into the fine matrix.

Rock fragments occur abundantly and both the coarse and fine-grained varieties can be distinguished in this fraction also. Some of these show indistinct outlines and merge into the matrix, but the number of such occurrences is rather small. Two such grains are seen in Plate 8, Fig. 1 on the right and left hand sides and one in Plate 8, Fig. 2 in the central part.

Micas are present in all the samples and show the same general characters as in the basal horizon, but some patches of fresh biotite flakes are noteworthy. Plate 9, Fig. 2 shows a cluster of fresh, highly pleochroic biotite in which the flakes are curved and compressed. Some flakes seen at the centre of the cluster are distinct and show perfect cleavage, but many at the periphery are indistinct and hardly distinguishable from the chloritic matrix in the upper right-hand and lower left-hand portions of the figure. From their nature and close association with the chloritic matrix, it appears very likely that these patches of fresh biotite are the product of recrystallisation of the matrix and are not detrital in nature.

Among the minor accessories, garnet, actinolite-tremolite, zircon, epidote, and opaque minerals are common but tourmaline was not observed in any thin section. A detailed description of the accessories would appear in the following pages.

The most distinctive component of this fraction is the matrix which though present in a much smaller amount as compared to the basal horizon , shows the same general characters as that of the basal boulder bed. It has already been shown that the matrix has been derived partly from the crushing of the shale and slate fragments and that it is considerably re-crystallised as a result of which many constituents of the framework have been marginally replaced. This is clearly seen in Plate 9, Fig. 3 where a large quartz grain has been deeply corroded by the matrix. The extent of replacement can be visualised from the original grain boundary which is very faintly visible along the left-hand edge of the figure. Similar replacement is also seen in the lower right-hand corner in Plate 8, Fig. 4 where a coarse-grained rock fragment has been penetrated by an inlet of the matrix. A magnified view of this inlet appears in Plate 9, Fig. 1 which clearly exhibits the manner in which the matrix has replaced the rock fragment.

The above study shows that the fine fraction of the upper boulder bed also is texturally and compositionally immature, but not to the same extent as that of the basal horizon. In view of the abundance of rock fragments in this fraction, its composition may be described as lithic graywacke.

Cross-bedded horizons

The cross-bedded horizons which occur enclosed in the upper boulder bed are remarkably different from it in colour and texture but have essentially the same overall composition. The cross-bedded units which are from 6 inches to 3 - 4 feet in thickness are not persistent over long distances, but merge gradually into the upper boulder bed. These units are mostly grey to dirty white in colour and the fine fraction has a sandy appearance. They are conglomeratic and have an arkosic, sometimes a lithic sub-graywacke-like matrix.

In thin sections they show much variation in their texture and composition. Two important textural varieties are illustrated in Plate 10, Figs. 1 - 4. Figs. 1 and 2 show a moderately well sorted rock with its framework intact and with less than 10% matrix. The constituents of the framework show much variation in roundness. Quartz grains are mostly angular as seen in the upper right-hand corner of Fig. 1, but felspar grains appearing in the centre near the lower edge of this figure are rounded. A fragment of graphic granite just above ti are sub-rounded to sub-angular.

Another variety, shown in Plate 10, Figs. 3 and 4, is very poorly sorted and contains upto 25% of matrix in Fig. 3 and about 18% in Fig. 4. The constituents of the framework in both the rocks are sharply angular to rounded depending on the nature of the fragments. Quartz grains in both the rocks are sharply angular while felspar grains are angular to sub-rounded. Rock fragments are generally sub-rounded to rounded as seen in the upper left-hand side of Fig. 3. A large grain of garnet in the top left-hand corner of Fig. 4 is rounded but grains of epidote and garnet in the lower right-hand corner are sub-rounded to angular.

Texturally the two types of rocks just described are quite different-the first illustrated in Plate 10, Figs. 1 and 2, comes from the middle part of the cross-bedded unit, while the second shown in Plate 10, Figs. 3 and 4, represents a transition between the boulder bed and its enclosed cross-bedded units.

The modal composition of the two types of fine fractions is shown in Table 16.

The general characters of the minerals are essentially the same as described earlier. Quartz is the most dominant mineral in the first type

TABLE 16: MODAL COMPOSITION OF THE CROSS-BEDDED HORIZONS (PER CENT)

Coalfield	S.No.	Quartz	Felspars	Rock fragments	Micas	Minor accessories	Matrix
North Karanpura	1	52.22	23.64	11.91	....	3.91	8.32
	2	46.64	14.00	24.60	....	2.41	12.35
	3	45.21	19.03	16.08	....	2.29	17.38
	4	42.05	16.42	15.79	1.08	3.57	21.09
Bokaro	5	49.81	23.23	13.75	....	1.99	11.22
	6	32.97	20.36	28.73	1.18	2.30	14.46
	7	41.61	15.63	18.09	0.29	1.52	22.86
	8	50.11	10.48	12.39	0.97	3.42	22.63
Jharia	9	41.61	20.23	23.49	....	2.42	12.25
	10	50.74	22.85	16.92	0.64	3.73	5.12
	11	43.79	18.56	17.83	....	2.68	17.14
	12	30.64	25.72	16.78	1.29	1.86	23.71

and its amount varies from 32.97% to 52.22%. The percentage of felspars and rock fragments varies from 14.00 to 23.64 and 11.91 to 28.73 respectively. Biotite and muscovite are poorly represented in this variety and their amount varies from nothing in most samples to 1.18%. Minor accessories, however, tend to be concentrated in this horizon and their amount varies from 1.99% to 3.91%. The fine grained detrital matrix, though showing the same overall characters as in the fine fractions of the two boulder beds, is very much reduced in quantity and fills up the voids left between the grains; its percentage varies from 5.12 to 14.46.

This variety can be divided into two types. One in which the felspar content is high and exceeds the rock fragments can be best designated as an "Arkose"; the other showing an abundance of rock fragments over the felspars resembles closely a lithic sub-graywacke.

The second variety of the fine fraction of the cross-bedded horizons shows a comparative abundance of the fine grained detrital matrix, although the quantity of this component varies considerably. This type is truly a transition between the cross-bedded horizons and the enclosing upper boulder bed.

H E A V Y   M I N E R A L S

Heavy minerals are the minor accessories of sediments that have a greater specific gravity than bromoform (2.87) and represent the stable and more durable constituents of the parent rock. Suits of heavy minerals have been widely employed for correlating sedimentary strata and also for determining their provenance. Their interpretation is complicated owing to the fact that the nature of the ultimate assemblage depends on several factors, important among these being the composition of the parent rock and the stability of the individual mineral species (Boswell, 1933, pp. 37-46).

No studies of the heavy mineral contents of the Talchir boulder bed have been made by any earlier worker, although sandstones of the Talchir series were studied with respect to this characteristic in parts of the Jharia and East Bokaro coalfields (Jacob and others, 1958) and in the Giridih basin (Rao, 1957). The purpose of the present study, therefore, was to provide a basic data on the nature of the heavy minerals contained in the fine fraction of the boulder bed in the area under investigation and to determine if these could be used for distinguishing the various horizons of the boulder bed. Since no correlation was desired, only the 1/8-1/16 mm. grade (very fine sand) fractions have been examined for their heavy mineral contents thereby ignoring the effects of granular variation (Rittenhouse, 1943; Van Andel, 1950). This study has proved greatly helpful in determining the provenance of the material constituting the boulder bed.

Analytical procedure

About 25-30 gms. of the very fine sand fraction (1/8-1/16 mm.), obtained earlier during mechanical analysis, was taken by splitting the entire fraction by a Jones' type of splitter and was digested in 1 N hydrochloric acid to remove the coating of iron oxide around the grains. The sample was then dried and accurately weighed.

The heavy minerals of the cleaned samples were separated according to the method suggested by Krumbein and Pettijohn (1938, pp. 343-44, Fig. 153) using bromoform of specific gravity 2.87 as the separating liquid. After the separation was complete, both the heavy and light fractions were washed with alcohol, weighed and stored separately. As the crop of the heavy minerals from each sample was large, it was split till about 1000 grains were obtained using a simple technique suggested by Hutton (1950, p. 643). The residues thus split down were permanently mounted in canada balsam (1.54).

Percentage of Heavy Minerals

The percentage by weight of the heavies in the samples from the various horizons of the boulder bed shows some interesting trends. Table 17 shows the average weight percentage of the heavies based on 39 analyses.

TABLE 17: WEIGHT PER CENT OF HEAVY MINERALS IN THE 1/8 - 1/16 MM. GRADE

H O R I Z O N	C O A L F I E L D					
	N. Karanpura	S. Karanpura	Bokaro	Ramgarh	Jharia	Raniganj
Basal boulder bed	3.30	2.15	3.20	3.30	3.12	2.98
Upper boulder bed	8.50	....	2.75	1.55	1.25	....
Cross-bedded Horizons	10.00	....	1.32	....	....	.....

In the basal boulder bed the average quantity of the heavy minerals is almost uniform in all the coalfields varying from 2.15 to 3.30% by weight of the sample. The upper boulder bed, however, shows a sharp decline in the average percentage of the heavies from 8.50 in the North Karanpura to 1.25 in the Jharia coalfield. In the cross-bedded horizons the decrease in the percentage of the heavies is very sharp, from 10.00 in North Karanpura to 0.92 in the Jharia coalfield.

Heavy Mineral frequencies

The determination of the heavy mineral frequencies is necessary for any systematic study where it is desired to obtain the relative abundance of the various species. Various descriptive terms and symbols have been devised for describing the abundance of minerals (Boswell, 1923; Milner, 1929), but for most quantitative studies actual counting of grains is necessary (Fleet, 1926). Dryden (1931) suggested that counting of 300 grains in each slide is enough for an accurate study and that counting a larger number of grains does not increase the accuracy in the same proportion. In the present study 300 grains per slide were counted and the scale devised by Evans and others (1933) was used for the determination of heavy mineral frequencies of the various samples. The scale is shown in Table 18. As is seen from the table, the scale is logrithmic down to frequency of 3 but is more or less arbitrary for lower values. It has, therefore, the advantage of bringing out more clearly the small variations in the lower frequencies which are more important than the large variations in the higher frequency values.

TABLE 18: LOGRITHMIC FREQUENCY-NUMBER SCALE OF EVANS, HAYMAN AND MAJEED (1933).

Frequency	Percent	Term
8+	90-100	Very abundant
8	75-89	
8-	60-74	
7+	45-57	
7	35-44	Abundant
7-	28-34	
6+	23-27	
6	18-22	Fairly abundant
6-	13-17	
5	7-13	Very common
4	4-6	Common
3	2-3	Fairly common
2	1-2	Scarce
1	½-1	Rare
1-	1 grain only per slide	
0	0	Absent

TABLE 19: HEAVY MINERALS OF THE BASAL BOULDER BED

Coalfield	Garnet	Epidote	Zircon	Tourmaline	Micas & Chlorite	Rutile	Stauro-lite	Opaques
	8-	6-	5	4	1	1	1	3
North Karanpura	7+	6+	4	2	2	1	1	4
	7+	7-	4	3	4	1	1	5
	7+	6	4	3	0	1	1*	6
South Karanpura	7	6+	4	3	2	1*	0	4
	7+	6+	4	4	2	1	1	5
	7+	7	5	2	3	0	0	6
Bokaro	7+	7-	5	2	3	1	1*	5
	7	6	4	3	2	1	1	6
	7-	6-	5	3	4	1*	1*	6-
Ramgarh	7	6-	4	4	3	2	1	5
	7+	7	5	3	3	1	1	6-
	8-	6	4	2	0	1*	0	3
Jharia	7	7-	5	2	1	1*	0	3
	7	6	5	2	3	1	1*	2
	7+	6	4	2	0	1	0	4
Raniganj	7-	6	5	2	2	1	0	3
	7	6-	4	4	1	2	1	4

TABLE 20: HEAVY MINERALS OF THE UPPER BOULDER BED AND THE CROSS-BEDDED HORIZONS

Coalfield	Garnet	Epidote	Zircon	Tourmaline	Micas & Chlorite	Rutile	Staurolite	Opaques
UPPER BOULDER BED								
	5	7+	6−	5	5	1	0	5
North Karanpura	7−	6	6−	5	3	0	1*	4
	7	6−	6	4	3	0	0	6−
	7	6	5	4	4	0	0	4
Bokaro	7	6−	6	5	5	0	0	5
	7+	5	4	5	5	1*	1*	5
	7+	3	6	5	3	1	0	5
Ramgarh	7+	4	5	4	4	1	1	6−
	7−	3	6−	4	4	0	0	5
	8	3	4	3	3	1	1	5
Jharia	7+	1	3	4	2	0	1*	4
	8−	3	3	3	2	1	0	5
CROSS-BEDDED HORIZONS								
	7+	6−	4	5	2	1	1	5
North Karanpura	7+	6	5	4	3	0	0	5
	7−	5	5	5	2	1*	0	6−
	6−	6	5	5	7	0	0	4
Bokaro	6+	6−	5	5	3	1*	0	6−
	7−	5+	6−	4	4	0	0	5
	7	4	6−	6+	4	0	1*	5
Jharia	7+	3	6−	6	2	1	0	5
	7+	3	5	6	3	0	0	6−

Table 19 shows the distribution of heavy mineral frequencies in the basal boulder bed. It is clear that this horizon shows a very uniform pattern of the heavy mineral frequency distribution throughout the Damodar Valley Coalfields. The frequency distribution of the heavies in the upper boulder bed and the cross-bedded horizons is shown in Table 20. In both horizons the mineral species and their frequencies are similar and show a uniform pattern throughout the Damodar Valley Coalfields.

Mineralogy

The heavy mineral crops in the various horizons of the boulder bed are rich and varied and consist of the following species:-

1. Actinolite-tremolite. The two amphiboles occur persistantly and in considerable quantity in the upper boulder bed and the cross-bedded horizons but are entirely absent from the basal bed. The grains are light bluish-green in colour and occur as short prismatic crystals with perfect cleavage. Pleochroism is feeble but distinct. Grains are sharply angular, have a chipped appearance and many of them show etching effects specially at the ends.

2. Epidotes (Pistacite, Clino-zoisite and Zoisite). Epidotes occur as sharply fractured grains which are very often altered. Pistacite, the most abundant variety, is greenish yellow and shows a weak but distinct pleochroism and high birefrengence. The other two varieties show their usual characters and occur as angular to sub-rounded grains.

Epidotes are of more common occurrence in the basal bed as compared to the upper one and the cross-bedded horizons. The majority of the grains show the "compass-needle" interference figure.

3. Garnet. Three varieties of garnets are distinguishable which together constitute the most abundant species of the heavy mineral fraction in all the coalfields of the Damodar Valley. The colourless variety is most abundant and is closely followed by the light pink variety, but the brown variety is rather rare. The grains are angular, sharply chipped and show conchoidal fracture in the basal bed but are better rounded in the upper bed and its cross-bedded horizons. The grains often show a pitted surface but etching is uncommon.

4. Micas and Chlorite. The distribution of the micaceous mineral is erratic in the various samples. In the basal bed they are absent to common but in occurrences of the upper bed and its cross-bedded units there is an abundance of these minerals. On the whole they are of more common occurrence in the upper boulder bed and its cross-bedded units as compared to the basal bed. Among the micas, muscovite is predominant and shows its usual characters. Biotite occurs in dark brown, blotchy, irregular cleavage flakes. Chlorite shows blotchy green colour, irregular shape and very weak birefrengence.

5. Opaques. Among the opaques both magnetite and ilmenite have been included and no attempt has been made to distinguish between the two. The grains are irregular, black and opaque and are common to fairly abundant in all the horizons of the boulder bed.

6. Rutile. Rutile occurs rarely, but persistently, in the basal boulder bed but is very often absent from the upper bed and the cross-bedded horizons. The grains are generally irregular to oval and are deep brown in colour.

7. Staurolite. Grains of this mineral are irregular showing a marked hackly fracture and numerous inclusions. They are yellowish brown in colour and distinctly pleochroic. This mineral is rarely present in the basal bed and does not appear at all in the upper boulder bed and the cross-bedded horizons.

8. Tourmaline. The brown and bluish varieties of tourmaline are most common and are strongly pleochroic. It is a common heavy constituent of the basal bed where it occurs as angular to sub-rounded grains. It is rare or absent in the upper bed and its cross-bedded horizons. Authigenic overgrowths in optical continuity with the detrital grains are often observed.

9. Zircon. This mineral is common to fairly abundant in all the horizons of the boulder bed. These grains show a great variation in their outlines and every gradation from well formed crystals to well-worn grains is seen. More commonly the zircons of the basal horizons are comparatively better rounded. Authigenic overgrowths on detrital zircon grains occur occasionally but are not very common. Inclusions of dark brown prismatic grains of rutile, magnetite and fine black dust are common.

CHAPTER V

FABRIC ANALYSIS

The term 'fabric' was first introduced to the English scientific literature by E.B. Knopf (1933) as an analogue to the German term 'Gefüge'. Fabric may be defined as the orientation in space of the constituents of which the rock is made. An object having no singular axis cannot possibly have any orientation because all positions would be alike but a non-spherical object has an orientation. The fabric is 'isotropic' when the orientation of the fabric elements is random and there is no direction preferred over the others. On the other hand if a certain direction is predominant and is preferred to all others, the fabric is then described as 'anisotropic' and the constituents are said to exhibit a 'preferred' orientation.

Three types of fabric can be distinguished in rocks depending on whether the directional properties of its constituents have originated by deformation, growth or deposition. A 'deformation' fabric is the result of outside pressure on the rock whereby its constituents acquire a given orientation. A 'growth' fabric is the consequence of crystallisation in situ. An 'opposition' fabric or 'sedimentary' fabric is developed by the orientation of the fabric elements during the deposition of a sediment under the influence of the depositing agency. It records faithfully the dynamics of the depositing medium and its careful study may reveal the direction of sediment transport and may be of immense value in reconstructing the palaeogeography of past ages.

METHODS AND INTERPRETATIONS

A review of the geological literature shows that fabric studies have been made in the past on almost all kinds of sediments, but the number of such studies is rather small. This arises out of the fact that fabric studies are tedious, time consuming and till recently there was no complete agreement regarding the interpretation of the fabric patterns. For the purpose of the present investigation, fabric studies on fluvial gravels and tills are of interest and as such only these two have been discussed in the following pages.

Fluvial Gravel Fabric

Becker (1893) seems to have been the first to study the orientation of pebbles in gravel deposits. He noted that the oblate pebbles show an upstream imbrication while the prolate particles tend to lie with their long axes perpendicular to the direction of current. This view was contradicted by Johnston (1922) who stated that the long axes of coarse particles lie parallel to the direction of the depositing agency. Twenhofel (1926) and Fraser (1935) challenged the opinion expressed by Johnston but they agreed with the view held by Becker.

These studies were mainly based on observations rather than actual measurements. The first attempt to make a quantitative study of the fabric of gravels was made by Wadell (1936) who measured the orientation of the long axes of pebbles in an esker and an outwash delta. He concluded that the pebbles in an esker dip in the same direction as the beds while in deltas in an opposite direction. In both cases the long axes were preferentially oriented in a direction parallel to the current. Wadell (loc. cit.) presented the orientation data on polar coordinate paper and constructed histograms for the purpose of interpretation. The method devised by him for the collection of oriented pebbles and their reorientation in the lab. is simple, though time consuming. Each pebble after being marked with a vertical and horizontal line in the field, is dug out of the enclosing matrix and reoriented in the laboratory on a two circle goniometer. The azimuth and inclination of the particle is then read and plotted as desired.

Cailleux (1938) also made a detailed study of the fabric of fluvial gravels and noted that the long axes of pebbles were preferentially oriented parallel to the current direction.

Krumbein (1939) studied the orientation of pebbles in glacial outwash deposits and found that the 'a' axes of a great majority of pebbles lie parallel to the direction of sediment transport. For the collection of oriented pebbles in the field and their reorientation in the laboratory, he adopted a simplified and a quicker version of the Wadell method.

Krumbein (1940, 1942) subsequently made extensive orientation studies on the flood gravels of two Californian streams, San Gabriel and Arroyo Seco.

In both cases he noted a strong upstream imbrication of the pebbles and a tendency for the long axes to lie parallel to the valley trend. Numerous secondary maxima at an angle to the valley trend are observed in his petrofabric diagrams.

White (1952) arrived at essentially the same conclusions as those by Krumbein. He noted that the pebbles in a Keweenawan conglomerate were inclined upstream and had a normal distribution about the mean. He, however, observed that some pebbles were inclined about 40° to the bedding and argued that their deposition took place in scour pits.

In 1953, Murray and Schlee (Schlee, 1957, p. 166) examined the fabric of some recent gravels of the Patapsco and Patuxent rivers and confirmed the conclusions drawn earlier by Krumbein (1939, 1940, 1942).

Schlee (loc. cit.) made an extensive study of fluvial gravel fabric with a view to make a quantitative study of pebble orientation and its relation to the valley trend. He made measurements on disc- and rod-shaped pebbles and concluded that the flat pebbles imbricate upcurrent with their short axes dipping down stream at steep angles, while "rod-shape pebbles show a peripheral semicircular arrangement of the maxima, the bisectrix of which points in the down current direction and point minima are present adjacent to the ends of the semicircle". He further stated that there was a tendency for the maxima "to lie on or adjacent to a plane which dips upcurrent (dip ranges from 10°-18°). The maximum dip azimuth of this hypothetical plane coincides in sense with the bisectrix mentioned above though in the opposite (upcurrent) direction". These conclusions based on the studies of modern streams are of far reaching importance as they practically set at rest the controversy regarding the attitude of pebbles to the valley trends. The technique adopted by Schlee is simple and quick but it is applicable only to unconsolidated or poorly consolidated deposits.

Till Fabric

Orientation studies on tills also have not received much attention for the same reasons as enumerated earlier. Richter (1932) made a quantitative study of the orientation of pebbles in some German tills. He measured the azimuth of their long axes and the data so obtained was plotted as histograms; the modal class was taken to indicate the direction of ice movement. Richter (1936) further elaborated his studies presenting the data in petrofabric diagrams.

Holmes (1938) devised a new field technique for the orientation of pebbles in tills and the data was plotted in modified star diagrams.

Krumbein (1939) studied the preferred orientation of pebbles in glacial till and found that the 'a' axes of a great majority of pebbles lie parallel to the direction of ice movement. He made a statistical analysis of the orientation data and noted that glacial outwash deposits show poor orientation of both the 'a' and 'c' axes as compared to the tills.

Holmes (1941) made a comprehensive study of till fabric in the

State of New York. His studies show that during transportation by the ice, the long axes of pebbles tend to be oriented perpendicular to the flow lying in a horizontal plane, but during deposition at the ice-till contact the pebbles rotate about their intermediate axes and tend to lie with their long axes parallel to the direction of ice movement roughly in a horizontal plane. Holmes also noted that the long axes have a minor tendency to be concentrated perpendicular to the glacial movement. His studies have further demonstrated that the nature of alignment of the pebbles (parallel or transverse), is also dependent on the inclination of the intermediate axis of the pebble. In this way he concluded that particles whose intermediate axes are inclined more that 75^o tend to be aligned perpendicular to the ice flow, while those with an inclination of less than 70^o prefer a parallel orientation.

Karlstrom (1952) devised an improved technique for the measurement of orientation of large sedimentary particles. After selecting a straight vertical face on the outcrop an orientation template is held parallel to it and the pebbles are properly marked with a pencil. The marked particles are reoriented on a two-circle goniometer. The azimuth and inclination of the long axes of particles is then read and recorded.

Dreimanis and Reavely (1953) made a study of the "alignment of stones" in tills along the north shore of the Lake Erie, using Richter's (1932) method. Separate measurements were made on particles with intermediate axes dipping less than 70^o, and those with more than 75^o, as suggested by Holmes (1941, p. 1319-1322). The results of their study confirmed the view expressed earlier by Holmes (1941).

Harrison (1957) studied the fabric in "shale loaded clay-tills" of the Chicago region. Oriented cubes of the till were collected in the field and were reoriented in the laboratory on a large two-circle goniometer. Measurements on the maximum projection planes of disc-& blade-shaped particles were made and their poles plotted on equal area polar net. The data was also plotted in petrofabric diagrams. These studies show that "the long axis parameter of rod-shaped particles tends to lie in a horizontal plane in the ground moraine or to be preferentially imbricated slightly (20°-25°) upstream to the former glacier-movement direction". The author used the features of the till fabric in explaining its origin and concluded that "the bulk of the ground moraine fabric is inherited, with only a slight degree of modification, from that fabric which is developed in the transportational environment".

So far as is known to the author no orientation study of gravels or tills have been undertaken in India except that by Ganju and Srivastava (1959) which was of an exploratory nature and confined to the Jharia coal-field only.

The technique adopted in the present study for the orientation measurements of the fabric elements differs considerably from that of other workers and is essentially a modification of the method used earlier by Ganju and Srivastava (loc. cit.). The more conventional methods of measurement could not be used for this study because of the peculiar nature of the outcrops of the boulder bed. This horizon forms flat grounds and good exposures occur mainly in shallow stream beds or on gentle slopes. Vertical faces of the exposures are extremely rare and thus the methods of Wadell, Schlee or Karlstrom could not be used for measurement purposes. Moreover, it was not possible to carry the pebbles in large numbers to the laboratory because of very difficult transport conditions. The measurements, therefore, had to be completed entirely in the field.

To overcome the effects of shape and size of pebbles on orientation (Cailleux, 1945; White, 1952; Brinkman, 1955; Harrison, 1957; Schlee, 1957), only the rod-shaped pebbles measuring 2 inches to 8 inches were selected for measurement. The choice was made primarily for the reason that this type was fairly abundant and the measurement of their long axes was a quicker process. Further, only those particles having intermediate axes dipping less than 45° (Holmes, 1941; Dreimanis and Reavely, 1953) were measured so that distinction could be made between the parallel and transverse maxima in the fabric diagrams.

The number of measurements at individual outcrops of the boulder bed varied from a minimum of 100 to a maximum of 300 depending upon the availability of suitable particles. The minimum of 100 measurements at a given locality was considered enough to determine statistically the direction of sediment transport as suggested by Karlstrom (1952, p. 489 footnote). Studies of Holmes (1941, p. 1308), however, indicate that even 50 till particles are enough to yield significant statistical results. A total of 3000 pebbles as shown in Table 21 were measured in the various coalfields.

TABLE 21: DISTRIBUTION OF ORIENTATION MEASUREMENTS

Coalfield	Locality	Number of measurements		
		Basal boulder bed	Upper boulder bed	Cross-bedded horizon
North Karanpura	West of Raie station	200	...	...
	East of " "	200	...	...
	West of Raie village	...	300	...
	East of Teleadih	...	...	300
South Karanpura	South of Chapri	100	...	...
West Bokaro	Dudhi river	100	...	...
	Tributary of Dudhi river	...	100	...
Ramgarh	West of Pooru	200	...	...
	Along the road west of Pooru	...	200	...
	Bhera river	...	300	...
	N-W of Dhavaiya	100	...	...
East Bokaro	Near Chapri	...	...	200
Jharia	Jamunia river	100	...	...
	Bansjor section	100	...	...
	East of Chandrapura station	...	200	...
	East of Tetulmari station	...	100	...
Raniganj	North of Tetulia	200	...	...
	Total ..	1,300	1,200	500

The procedure adopted for orientation measurements of the selected particles is as follows:-

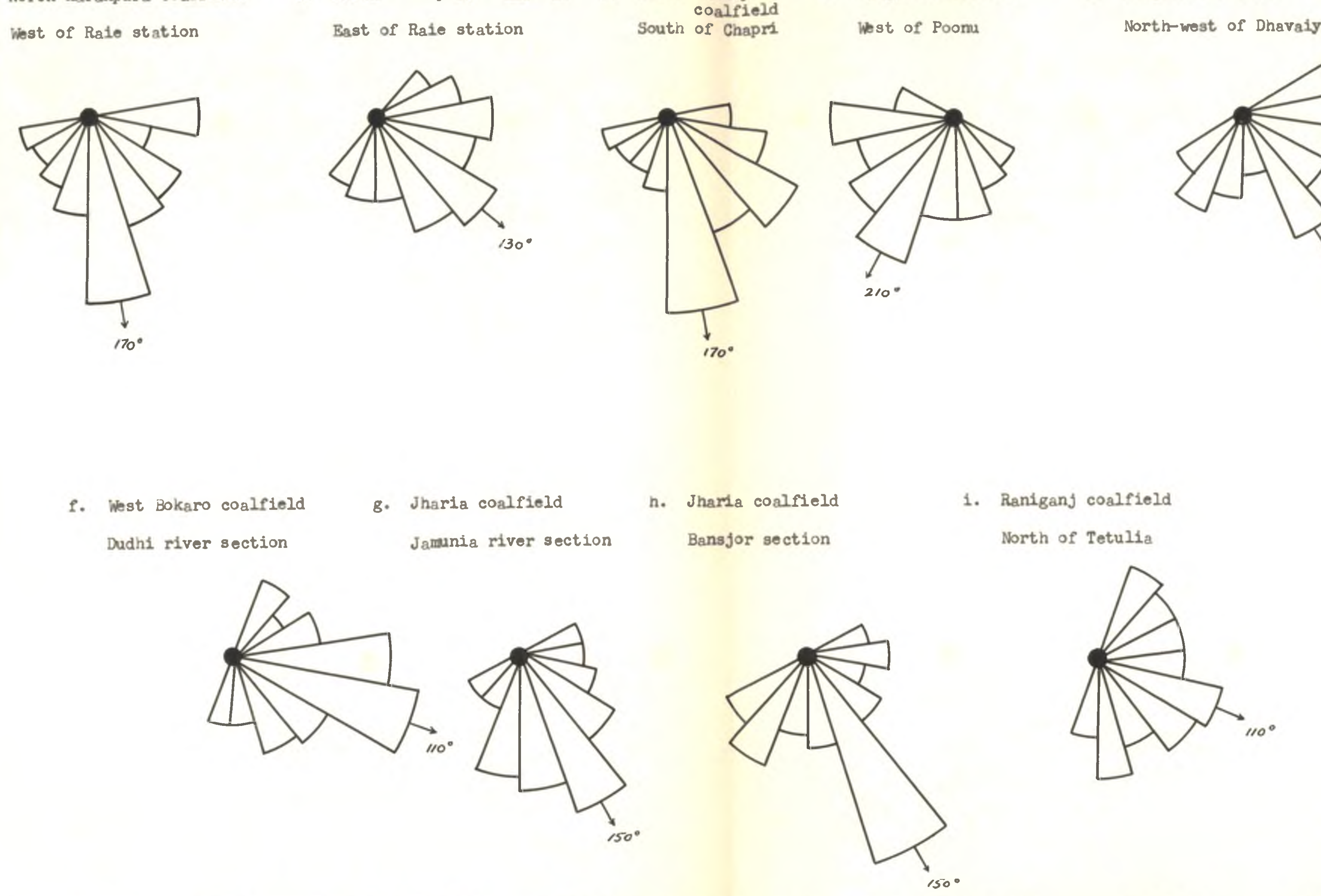
Each selected pebble was carefully taken out of the matrix, great care being taken not to disturb the matrix below the pebble. In most cases this operation was easy as the matrix was not very hard, but where it was hard, the pebbles were carefully chiselled out. As a rule the pebbles left their impression in the enclosing matrix. After removing the pebble and marking on it the points of emergence of the long axes with a piece of chalk, the pebble was fitted back into its original position. A pencil was then held parallel to the line joining the two chalk marks and its azimuth and inclination were measured with a clinometer compass.

PRESENTATION OF THE ORIENTATION DATA

The azimuth and inclination of the long axes of the measured particles were tabulated for each outcrop separately. The data was then presented both as semicircular histograms and as petrofabric diagrams for easy visualisation and interpretation of the orientation characteristics.

Semicircular histograms

The particles at each locality were first classified into eighteen 20-degree azimuth classes and frequencies were determined in each class. The frequencies in the corresponding classes opposite to each other on the



. 10. DISTRIBUTION OF 'a' AXIS AZIMUTHS OF ROD-SHAPED PEBBLES AND COBBLES OF THE BASAL BOULDER BED. FREQUENCY PER CENT PLOTTED IN 20-DEG
CLASSES. ARROW INDICATES POSITION OF MODE.

circle were then added together to give combined frequencies and the data so obtained was plotted as semi-circular histograms using 20° classes. For the sake of simplicity and for providing greater symmetry, the modal class in each case was made to coincide with the centre of the histograms by re-arranging the tables.

Fig. 10 (a-i) shows the azimuthal distribution of the 'a' axes of pebbles and cobbles from the different outcrops of the basal boulder bed. All diagrams except No. g, show a polymodal distribution of the azimuthal frequencies. Further, the frequency distribution on either side of the modal class does not taper off regularly. These features clearly show that the frequency distribution is not 'normal' (Hirsch, 1959, p. 51).

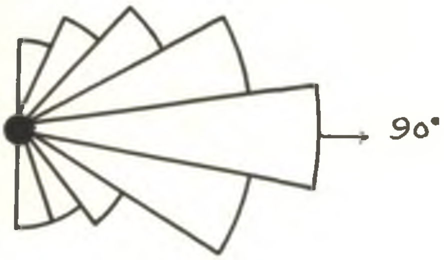
The position of the mode, taken as the mid-point of the modal class as a first approximation (Krumbein & Pettijohn, 1938, p. 273) is indicated by an arrow in each diagram. It is observed that the modal azimuths range from 110° in diagrams f and i to 210° in diagram d. In six cases out of nine, however, the mode falls between 130° and 170°, a range of only 40°. Out of these, three diagrams (e, g and h), show modes at 150°.

The modal class is conspicuous in diagrams a, c, d, f, g and h, while it is not so in others. The height of the modal class is a measure of the peakedness of the frequency distribution.

Fig. 11 (a-f) shows the azimuthal distribution of the long axes in the upper boulder bed. The frequency distributions in this horizon also are not "normal" except in No. a. The modal azimuths range from 30° to 110°

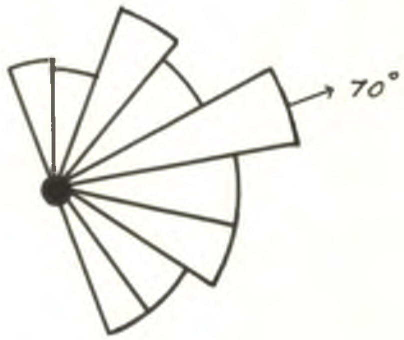
a. North Karanpura coalfield

West of Raie village



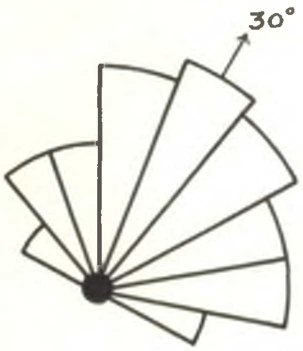
b. Ramgarh coalfield

Bhera river section



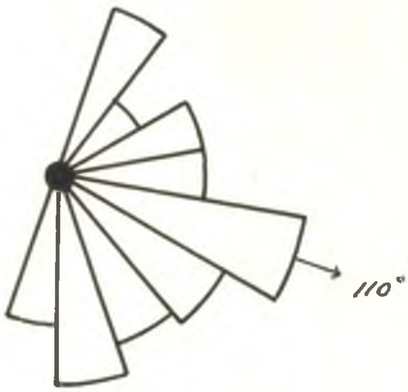
c. Ramgarh coalfield

West of Poonu



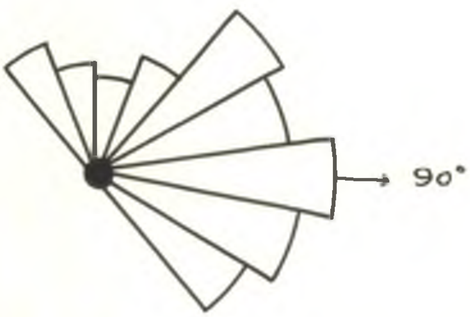
d. West Bokaro coalfield

Tributary of Dudhi river



e. Jharia coalfield

East of Chandrapura station



f. Jharia coalfield

East of Tetulmari station

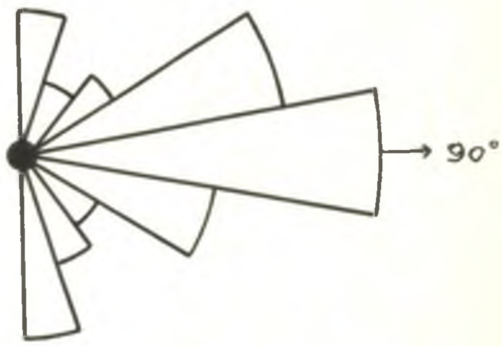
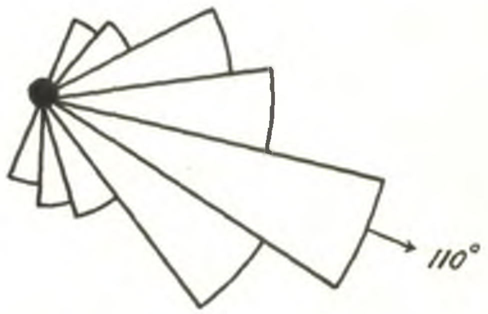


FIG. 11. DISTRIBUTION OF 'a' AXIS AZIMUTHS OF ROD-SHAPED PEBBLES AND COBBLES OF THE UPPER BOULDER BED. FREQUENCY PER CENT PLOTTED IN 20-DEGREE CLASSES. ARROW INDICATES POSITION OF MODE.

a. North Karanpura coalfield

East of Teleadih



b. East Bokaro coalfield

Near Chapri

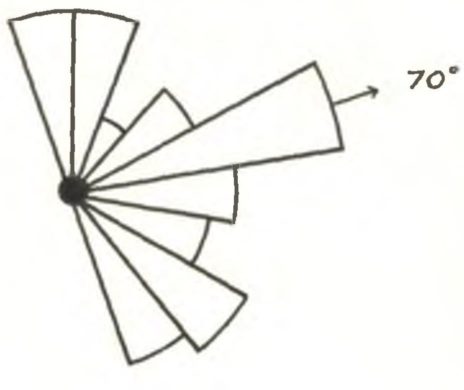


FIG. 12. DISTRIBUTION OF 'a' AXIS AZIMUTHS OF ROD-SHAPED PEBBLES AND COBBLES OF THE CROSS-BEDDED HORIZONS. FREQUENCY PER CENT PLOTTED IN 20-DEGREE CLASSES. ARROW INDICATES POSITION OF MODE.

but in 3 cases out of 6 the value is 90°. A range of 40° (70° - 110°) is covered by 5 diagrams out of 6. Only three diagrams (a, d, and f) show conspicuous peaks and in this resepct this horizon does not differ materially from the basal boulder bed. The cross-bedded horizons show essentially similar characteristics of the azimuth frequency distribution and this is clear from Fig. 12, diagrams a and b.

Petrofabric diagrams

Petrofabric diagrams take into account the azimuth as well as the inclination of the fabric elements and give a unified picture of the fabric pattern. These are superior in many respects to the histograms as means of presenting the data. Although such diagrams do not give the average direction of orientation in numerical terms, they do indicate a mean direction.

The data on the azimuth and inclination of the long axes of pebbles and cobbles was plotted on Schmidt stereo-net of 20 cm. diameter mounted on a turntable device. A tilt correction was made so that the attitude of the pebbles and cobbles at the time of deposition could be known. This was done by rotating the poles about the strike of the boulder bed or to that of the overlying strata by an amount equal to the dip of the bed.

The final density diagrams were prepared by contouring the point diagrams using a method first adopted by Schmidt (See Fairbairn, 1954, p. 285). The contouring was done with the help of three celluloid counters

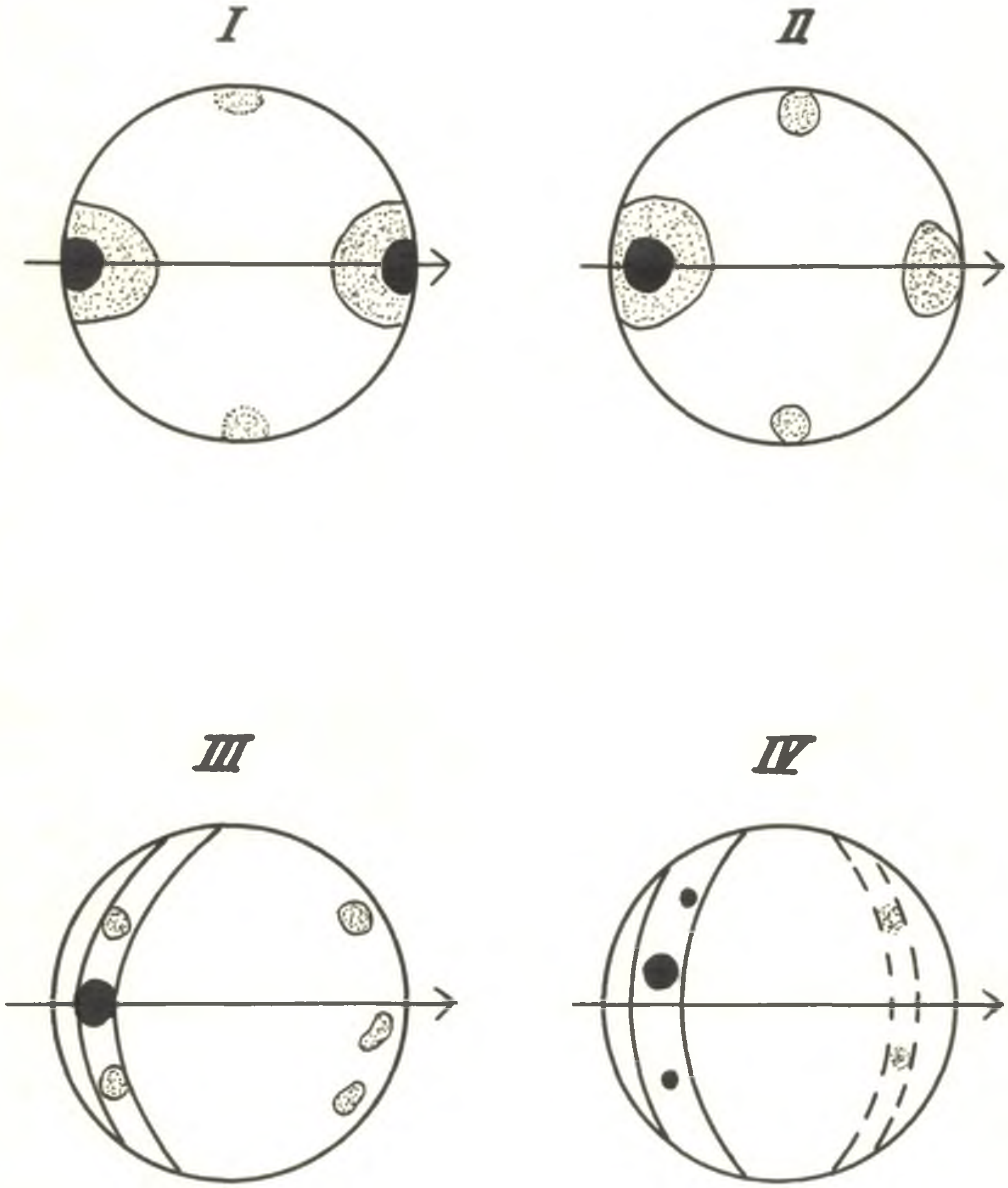


FIG. 13.

SCHEMATIC DIAGRAM SHOWING "TYPE" FABRIC PATTERNS with circular openings representing 1% of the total area of the net. The counters were moved systematically over a centimetre grid kept below the plotting sheet. The number of points within the 1% circle in the inner part of the diagram or the total number of points within the two circles on the margin of the standard circle, were counted. The value of the contour was then written at the intersection of the grid lines by determining the percentage of points in unit area. When all the grid intersections had been traversed in this manner, the diagram was contoured. A detailed description of this method has been given by Fairbairn (loc. cit. pp. 285-290).

A glance of the fabric diagrams of the boulder bed (Figs. 14-30) shows that no two are exactly alike. They differ from one another in their patterns as well as in the degree and direction of preferred orientation. Inspite of this, a few "type" patterns are clearly distinguishable and the various fabric diagrams can be broadly classified according to these types. The following type patterns shown graphically in Fig. 13, have been distinguished:-

I. Two poles in the bedding plane or in slightly dipping and diametrically opposite girdles with or without two transverse sub-maxima.

II. A single pole with a slight upcurrent dip with one diametrically opposite sub-maximum and two transverse sub-maxima.

III. A single pole and several sub-maxima in a girdle dipping upcurrent. Point minima are present at the two ends of the girdle containing the pole.

IV. Two or more poles in a girdle dipping upcurrent with or without another girdle dipping down current. Point minima are present at the two ends of the girdle containing the poles.

Figs. 14-22 show the three dimensional orientation patterns displayed by the selected fabric elements of the basal boulder bed. Of these, Figs. 15, 16, 17, 21 and 22 correspond closely to the type pattern II. The long axes of the particles show a preferred orientation and are imbricated upcurrent in Figs. 15, 21 and 22, while several sub-maxima occur in a girdle in Figs. 16 and 17. A smaller number of particles are oriented transverse to the preferred direction. The strength of the transverse maxima differs considerably in different cases. The fabric directions in these patterns have been determined by the position of the maxima.

Fig. 19 belongs to the type pattern I and shows two maxima and two transverse sub-maxima in the bedding plane. There is a slight tendency to imbrication. Fig. 18 is a modification of type I and shows two maxima in the upcurrent direction and two in the down current direction, but the transverse sub-maxima are absent. The fabric direction in Fig. 19 has been determined by the line joining the two maxima and in Fig. 18 by a line passing midway between the maxima in the direction of preferred orientation.

Fig. 14 corresponds to the type pattern IV. The maxima lie in a girdle dipping upcurrent and sub-maxima lie in another girdle dipping down current, but there are no transverse sub-maxima. The fabric direction has been determined by the bisectrix of the girdle containing the maxima. Fig. 20 is a modification of this type and shows four maxima lying in a semicircle.

considered intermediate between types I and II, although it resembles type II very closely. The long axes are preferentially oriented and lie almost in a horizontal plane showing conspicuous transverse maxima.

STATISTICAL TREATMENT OF THE AZIMUTHAL DATA

It is not always possible to determine whether or not preferred orientation is present in a given population of fabric elements by a mere visual inspection of histograms and fabric diagrams. A more rigourous method is, therefore, required to establish the presence of anisotropism or its absence. Further, the significance of the orientation data is best understood if it is summarised statistically.

In the present study a statistical analysis of the azimuthal data alone has been undertaken. As the direction of sediment transport can be inferred from the direction of preferred orientation, a statistical study of the dip angles was not made.

The Chi-square test

The chi-square test of significance has found wide application in the analysis of sedimentary data. The test can be used to determine the probability with which a given distribution of frequencies might arise from an isotropic parent population.

TABLE 22: ORIENTATION STATISTICS OF THE BASAL BOULDER BED

Coalfield	Locality	Fabric direction	Modal azimuth	Resultant vector azimuth	Chi-square
North Karanpura	1. West of Rais station	138°	170°	131°48'	32.09
	2. East of Rais station	112°	130°	129°00'	18.23
South Karanpura	3. South of Ghapri	136°	170°	175°24'	25.54
West Bokaro	4. Dudhi river	132°	110°	97°36'	21.91
Ramgarh	5. West of Pooma	225°	210°	139°18'	18.63
	6. North-west of Dhavaiya	143°	150°	203°00'	5.06
Jharia	7. Jamania river	160°	150°	117°12'	19.00
	8. Bansjor river	152°	150°	129°42'	23.00
Raniganj	9. North of Tetulia	129°	110°	66°48'	5.63

The value of chi-square for each sample has been determined by the formula:

$$\chi^2 = \frac{\Sigma(f-F)^2}{F}$$

where f is the observed frequency and F the expected frequency in each 20-degree class. Since all the classes are of equal size, F is same in all the groups and its value can be determined by dividing the total frequency by the number of classes which are nine in the present case. The number of degrees of freedom is given by subtracting 1 from the number of classes into which the frequencies have been grouped. In the present case, therefore, it is 8. The level of significance has been chosen at 0.05, that is, no distribution has been considered significantly different from randomness unless there is less than one chance in twenty of its being due to chance.

A glance at any standard table of critical chi-square values shows that for 8 degrees of freedom and at 0.05 level of significance, the critical value of chi-square is 15.51. If the calculated value of chi-square is greater than 15.51, we accept the hypothesis that the parent fabric is anisotropic; if the value is lower, it is rejected. It should, however, be noted that the rejection of the hypothesis does not prove isotropism of the parent population (Chayes, 1949, p. 300).

The chi-square values for samples from the basal boulder bed at different localities appear in Table 22. The values for samples from localities 1, 2, 3, 4, 5, 7 and 8 exceed the critical value at 0.05 level making it very likely that the parent population at these localities is anisotropic. The samples from localities 6 and 9 show very small chi-square values making it unlikely that the parent population in these two localities is anisotropic. Much reliance, however, cannot be placed on low chi-square values as these may reflect an improper sampling technique rather than isotropism of the parent fabric (Chayes, loc. cit. p. 300).

TABLE 23: ORIENTATION STATISTICS OF THE UPPER BOULDER BED AND THE CROSS-BEDDED HORIZONS

Coalfield	Locality	Fabric direction	Modal azimuth	Resultant vector azimuth	Phi-square
UPPER BOULDER BED					
North Karanpura	1. West of Hale village	90°	90°	106°48'	56.82
West Bokaro	2. Tributary of Dudhi river	98°	110°	118°52'	6.63
Ramgarh	3. Along the road west of Pooru	49°	30°	19°42'	14.73
	4. Bhera river	76°	70°	121°42'	13.97
Jharia	5. East of Chandrapura station	85°	90°	87°28'	16.45
	6. East of Tetulmari station	90°	90°	46°12'	30.09
CROSS-BEDDED HORIZONS					
North Karanpura	7. East of Telesdih	105°	110°	120°06'	52.18
East Bokaro	8. Near Chapri	73°	70°	45°20'	9.18

The chi-square values for samples from the upper boulder bed and the cross-bedded horizons at different localities appear in Table 23. The values for localities 1, 5 and 6 exceed the critical value at 0.05 level showing that the parent population in these localities is anisotropic and that the fabric elements show a preferred orientation. The values for localities 3 and 4 exceed the critical value at 0.10 level indicating that there are not more than 10% chances of the frequencies being drawn from an isotropic population. It is possible as is evident from the relevent histograms and fabric diagrams, that the fabric elements show a poor preferred orientation at these localities. The chi-square value for the sample from locality 2 is very small and probably reflects poor sampling.

The cross-bedded horizons in the North Karanpura coalfield show a strong tendency to preferred orientation, but the same horizon in the East Bokaro coalfield reveals lack of anisotropism.

The direction of preferred orientation

Once the anisotropic character of the fabric has been established, it is useful to know the direction of preferred orientation. This can be done either by mathematical methods or by an inspection of histograms and fabric diagrams. The choice of the method largely depends on the nature of the data in hand. In the present investigation both the methods have been applied and a comparative study of the two has been made in order to decide as to which method is more reliable.

The average direction of preferred orientation can be determined mathematically either by a moment analysis of the azimuthal data or by vector summation method. As the data in question are circularly dispersed and as the choice of the origin strongly influences the value of the mean (Jizba, 1953; Chayes, 1954; Curray, 1956; Pincus, 1956), the method of moment analysis was discarded in favour of the vector summation method as applied to circular frequency distributions (Reiche, 1938; Curray, loc. cit.; Pincus, loc. cit.).

The vector method consists of trigonometrically computing the N-S and E-W components of each group of unit vectors (Curray, loc. cit. p. 110) as follows:-

$$\text{N-S component} = \sum n\text{Cos}\theta$$

$$\text{E-W component} = \sum n\text{Sin}\theta$$

where n is the number of unit vectors in a group and θ is the mid-point of the azimuthal group. The azimuth of the resultant vector ($\bar{\theta}$) is given by:

$$\bar{\theta} = \text{arctan}\ \frac{\sum n\ \text{Sin}\ \theta}{\sum n\ \text{Cos}\ \theta}$$

The resultant vector azimuth is a measure of the average direction of preferred orientation and has the same significance as the mean calculated by moment analysis. Tables 22 and 23 record the vector azimuths of the samples from the basal and upper boulder beds and the cross-bedded horizons.

It has been shown earlier that histograms and contoured fabric diagrams can also be used to indicate the average direction of preferred orientation and it is interesting to compare the results obtained by the mathematical and the graphical methods.

The values of the average direction of orientation in the basal boulder bed as determined from the modal azimuth, fabric direction and the resultant vector azimuth appear in Table 22. The different values of the average direction show a lack of correspondance at any given locality. There is, however, a closer agreement between the modal azimuths and the fabric directions as compared to the resultant vector azimuths. The maximum difference between the former two is 34° at locality 3 but on the whole the differences are much smaller. Variation of the modal direction from station to station amounts to 100°, while it is 113° and 136°12' for the fabric direction and the resultant vector azimuth respectively. The arithmetic mean of the modal azimuths is 150°, while the mean fabric direction and mean resultant vector asimuth are 147°27' and 132°12' respectively. Once again a closer agreement between the mean modal and the mean fabric directions is apparent.

In the upper boulder bed, the station to station variations are of smaller order of magnitude as shown in Table 23. The fabric directions show a range of 49°, while the modal and vector azimuths show a range of 80° and 102° respectively. Broadly speaking there is a closer agreement between the modes and the fabric directions, the maximum difference between the two being only 19° at locality 3. The mean modal azimuth is 80°, and the mean fabric direction is 81°20', while the mean vector azimuth is 83°10'.

The same general statement holds good for the cross-bedded horizons of the upper boulder bed. The mean modal azimuth is 90°, while the mean fabric direction and resultant vector azimuth are 89° and 82°46' respectively.

The greater station to station variation of the resultant vector azimuths and their lack of correspondance with either the modes or the fabric directions can be accounted for by the fact that the azimuthal frequency distributions are not normal. The polymodal character of the frequency distribution interferes materially with the calculation of the resultant vectors. Under these circumstances the choice of the resultant vector azimuth as an index of the direction of preferred orientation is undesirable.

In the present case either the mode or the fabric direction can be taken to represent the average direction of orientation. However, mode has the most significant meaning in a unimodal frequency distribution (Krumbein and Pettijohn, 1938, p. 245). Further, the mode is also influenced by the class intervals used in the analysis and the same data might yield different positions of the mode depending on the choice of the class limits. For these reasons mode has not been taken as a true index of the preferred orientation direction in the present study.

The direction of preferred orientation as determined from the fabric diagrams is independent of the nature of the frequency distribution and the choice of the class limits. It takes into consideration the pattern of the fabric which truly reflects the character of the transporting agency. It is, therefore, a better and a more reliable measure of the central tendency of the frequency distribution and has been used in the present study as an index of the direction of sediment transport.

REGIONAL PATTERN OF THE FABRIC

The above study clearly shows that the fabric patterns of the basal and the upper boulder beds differ remarkably from one another. The basal boulder bed in all the coalfields of the Damodar Valley region shows close resemblance to types I and II of the fabric patterns. Of the nine fabric diagrams, seven belong to these two groups, while only two resemble the pattern IV. The fabric of the upper boulder bed, on the other hand, shows remarkable similarity to types III and IV, only one diagram out of six resembling type II. The cross-bedded horizons show variable fabric patterns.

In all the localities studied the long axes of the rod-shaped pebbles show a preferred direction of orientation. This direction is different in the two horizons of the boulder bed; the basal horizon shows an approximately NW-SE direction of preferred orientation, while the upper one shows an approximately E-W direction.

Although the degree of preferred orientation cannot be determined in numerical values due to the strongly sub-normal character of the azimuthal frequency distributions, it can be roughly estimated from the peakedness of the modal class of the histograms and also from the chi-square values. Figs. 10, 11 and 12 show that differences in peakedness between the basal and the upper boulder beds are not clearly defined. Chi-square values for samples from the different localities of the boulder beds indicate that preferred orientation is well established in the basal horizon but appears to be poor or even doubtful in many localities of the upper horizon. It may be concluded, therefore, that significant differences in the degree of preferred orientation of the long axes of rod-shaped pebbles do not exist among the different horizons of the boulder bed, but, broadly speaking, the basal horizon shows less scatter of the azimuthal data as compared to the upper bed and the cross-bedded horizons.

CHAPTER VI

ORIGIN OF THE TALCHIR BOULDER BED

The different views held regarding the origin of the Talchir boulder bed have already been summarised. Broadly speaking, four hypotheses have been advanced to explain the origin of this deposit. These are:-

1. That the boulder bed is a marine gravel or a near shore tallus deposit (Hughes, 1867; Ball, 1867).

2. That the material constituting the boulder bed was first rounded by mountain streams and then transported to the site of deposition by ground ice or floating ice (Blanford and others, 1856; Fedden, 1875; Blanford, 1887; Holland, 1933; Wadia, 1939).

3. That the boulder bed represents a true tillite (Oldham, 1893; Fermor, 1914; Simpson and Ball, 1922; Jowett, 1925; Jacob, 1952; Krishnan, 1958).

4. That the boulder bed represents a resorted moraine material and the "true Ice Age of Gondwana-land was earlier than the Talchir deposits as we find them today". (Fox, 1930).

The hypothesis that the boulder bed is a marine gravel or a near shore tallus deposit is untenable. The presence of striated and facetted pebbles, the occurrence of occasional fragments of quartzite and jaspar conglomerate of Vindhyan and Bijawar affinity and the abundance of a gray-wacke-like matrix clearly show that such a deposit could not have formed in a normal marine environment. It is interesting to note that Ball, a strong supporter of this view, changed his opinion (Ball, 1873, p. 28 foot-note) when he noted the occurrence of pebbles of Vindhyan age in the boulder bed of Bisrampur coalfield and concluded that these pebbles could be present only "through the agency of ice".

The view that the coarse material constituting the boulder bed was first rounded by fast flowing mountain torrents and then transported to the cite of deposition by the agency of ground ice or floating ice needs critical examination. The strongest evidence that has been cited in favour of this view is the occurrence of well rounded pebbles and boulders in association with clay and silt. According to Blanford and others (1867) "their much rounded condition seems quite opposed to the idea of transport by true glaciers".

The presence of rounded fragments, however, is no indication that the true glacial conditions were absent. It is obvious that the bulk of the debris transported by a glacier never comes in contact with either the bed rocks or the side walls and according to Von Engeln (1930, p. 15), the pebbles and cobbles retain their "original form quite unaffected by the ice transportation over a long trip". He further stated that "under these circumstances, a non-facetted, rounded, elliptical, cylindrical, in general ovoid, pebble is produced .... They are more abundant actually than the flat-iron types". It is thus clear that even in true glacial deposits there will be an abundance of rounded and sub-rounded pebbles, cobbles and boulders. This conclusion is also supported by the studies of Wentworth (1936 a, p. 96) who has stated that in a true glacial deposit "the majority of the cobbles have rounded and smooth edges".

Another evidence in favour of the hypothesis originally put forward by Blanford and others was given by Fedden (1875, p. 17). He pointed out that the boulder bed did not necessarilly occur at the bottom of the Talchir succession and that it was often "intercalated with very regular and sharply bedded deposits". This evidence again is not satisfactory because in areas where multiple tills occur, the individual sheets may be separated by varying thicknesses of sand, clay and silt. The studies of Shepps (1953) and Dreimanis and Reavely (1953) show that such cases are not uncommon.

The "ground ice" hypothesis was criticised by Oldham (1883), Fermor (1914), Simpson and Ball (1922) and Jowett (1925) on the ground that the boulder bed often contains smoothed and striated pebbles and that such features could be produced only by the agency of true glaciers. This criticism, however, does not appear to be valid because extensive studies of Von Engeln (loc. cit.) and Wentworth (1936 b) have clearly demonstrated that even river-ice transported fragments (ice-jam cobbles of Wentworth) bear faces and striations. The following differences noted by Wentworth (1936 b) are very useful in distinguishing glacial debris from that derived by the agency of ground ice:-

1. Crude, broad, short bruises are uncommon in glacial cobbles but are a characteristic feature in ice-jam cobbles

2. Curved striae merging with bruises and gouges are rare in glacial cobbles but are quite common in ice-jam cobbles.

3. Striations in glacial cobbles may occur both on plane facets and in moulded configuration on curved or doubly curved surfaces, while in river-ice transported cobbles they occur only in moulded configuration on curved or doubly curved surfaces.

4. Grid, random and scatter patterns of striae are less common and less distinct in glacial cobbles as compared to the ice-jam cobbles.

5. Parallelism between the striation pattern and the long axis is the preponderant and modal type in glacial cobbles, while in ice-jam cobbles this feature is not especially evident.

The present study shows that the surface textures of the pebbles and cobbles of the boulder bed are remarkably similar to those found in glacial deposits and bear no resemblance to "ice-jam" cobbles.

It may be concluded on the basis of the above evidence that in all probability, the Talchir boulder bed in the Damodar Valley Coalfields was not produced by the agency of ground ice. The above arguments also prove that the boulder bed is of ultimate glacial origin. It represents either an original moraine left behind by the ancient glaciers (Oldham, 1893; Fermor, 1914; Simpson and Ball, 1922; Jowett, 1925; Jacob, 1952; Krishnan, 1958) or a reworked glacial debris "turned over by flood action" (Fox, 1930). If the former view is correct, the boulder bed must show the characteristics of a tillite, but if the latter view is accepted, the boulder bed should exhibit the essential features of a fluvial gravel.

Before proceeding further, it is important to recall that two distinct horizons of the boulder bed, each separated from the other by 50-200 feet of shales and sandstones, occur in almost all the coalfields of the Damodar Valley. Detailed petrographic and fabric studies by the present author show that inspite of the superficial resemblance between the two horizons, the following important differences are clearly marked:-

1. On an average the pebbles and cobbles of the upper boulder bed and the cross-bedded horizons are better rounded as compared to those of the basal horizon.

2. About 5-10% of the coarse debris of the basal boulder bed are facetted and show "flat-iron" shapes, while only 1-3% are of this type in the upper horizon. Further, important differences between the two horizons of the boulder bed occur with respect to the shape characteristics of the large particles in terms of Zingg percentages.

3. The two horizons can be clearly distinguished on the basis of the mechanical composition of their matrix. The fine fraction of the basal bed is finer grained as compared to the upper bed. The two horizons also differ from one another in their sand, silt and clay contents.

4. The fine fraction of the basal boulder bed is characterised by the presence of a much larger quantity of the matrix and lower proportion of felspars and rock-fragments as compared to the upper horizon.

5. The heavy mineral suits of the two horizons show important differences, both in their quantity and quality.

6. The fabric of the basal boulder bed is comparable to types I and II, while that of the upper bed shows resemblance to types III and IV of Fig. 14. The fabric direction in the two beds is different and so also is the degree of preferred orientation.

The differences mentioned above indicate that the two beds have a different history and that they were not produced under the same set of geological conditions. It is for this reason that the problem of their origin can be best understood if the two beds are examined separately.

THE BASAL BOULDER BED

It has already been stated that the debris comprising the basal boulder bed is very poorly sorted and that it consists of an assortment of sharply angular to rounded pebbles, cobbles and boulders which lie in an abundant graywacke-like matrix. This horizon shows no stratification and the finely laminated varved shales overlying it contain rafted pebbles.

The quartzite pebbles enclosed in this horizon are sub-rounded to rounded, the variation in roundness values being from 0.472 to 0.566. These values are comparable to the average value of 0.54 given by Krumbein and Sloss (1951, p. 83) for glacial till pebbles. More remarkable, however, is the occurrence of about 5-10% "flat-iron" shaped pebbles and cobbles in this horizon. Their presence, even in a small number, "may be regarded as of diagnostic significance in determining the glacial or the non-glacial origin of conglomerates and tillites about which there is doubt" (Von Engeln, loc. cit. p. 15). In the words of Coleman (1926, p. XXXVI), "they are typical manufactured articles shaped and marked in unmistakable ways as the handiwork of craftsman ice .... the results are unmistakable, since no other process of nature gives similar shapes or similar surfaces".

The sub-parallel striation pattern on the smooth surfaces of the pebbles and cobbles of this horizon is characteristic. The parallelism of this pattern with the long axes of particles is also an important feature and is found to occur in almost all the striated stones. Wentworth (1936 a) found that in glacial deposits the index of occurrences of the sub-parallel pattern was 791 per 1000 cobbles and that of the pattern parallel to the long axis was 753 per 100 cobbles. He concluded that these two features may be regarded as typically glacial in origin. The same author (Wentworth, 1922 c) has also shown that striae on glacial pebbles are superficial markings and that they are easily removed if the debris is transported even for a small distance. In view of this evidence, the presence of striations on the pebbles etc. of the basal boulder bed assumes importance as it proves that the glacial debris was not removed far from the place of its original deposition.

The fabric of this horizon also supports this conclusion. About 78% of all the fabric diagrams belong to type patterns I and II, which are comparable to those given by Holmes (1941) and Harrison (1957) for undisturbed glacial tills. Two diagrams out of nine belong to type IV and their pattern is similar to that given by Schlee (1957) for fluvial gravels. It is clear from the above statement that the fabric of the basal boulder bed shows essentially the characters of an undisturbed till, but occasionally it may resemble that of fluvial gravels.

Identical results are obtained when the fine fraction of the boulder bed is examined. This fraction is very poorly sorted as the material is spread over 13 Wentworth grades. The size frequency distribution is polymodal in all cases and the modal class is inconspicuous, containing not more than 23.25% by weight of the whole material. Further, the sand and clay contents of this horizon vary from 43.06% to 60.95% and 3.93% to 12.13%

respectively. Sheppe (1953) determined that the variation in sand and clay contents for the Tazewell tills of Ohio is 42.0% to 60.0% and 11.0% to 24.0% respectively. Although the figures for variation in sand content compare very favourably, those for clay are rather small for the basal boulder bed. The paucity of clay in this horizon is also emphasised when the data is compared to that given by Dreimanis and Reavely (1953) for the Lower Tills along the north shore of the Lake Erie. The low clay percentage can be explained on the assumption that the original till was slightly reworked by water during its deposition. Since the sand content in this horizon does not differ much from the values given by other workers for true tills, it follows that the strength of the washing agency was so small that only the clay particles were removed.

The micropetrological study of this fraction also shows that the rock is texturally and compositionally very immature and is comparable to the matrix of tillites. The sharply angular nature of the heavy minerals, their comparatively high concentration and the presence of ordinarily unstable mineral species, such as actinolite, tremolite and epidotes, also support the above conclusion.

It may be concluded that the basal boulder bed is a true tillite and that the material constituting it has not been turned over by flood action as Fox (loc. cit.) had assumed. Melt waters seeping through the freshly deposited till were in all probability, responsible for winnowing away much of the clay content. There are indications that locally on a small scale, the till was reworked by glacial streams, thus imparting to it the characteristics of a fluvio-glacial gravel here and there.

Provenance

The lithology of the coarse fraction and the micropetrology and heavy mineral studies of the fine fraction throw considerable light on the nature of the rocks which have supplied the material constituting the basal boulder bed. The lithological composition of the coarse fraction shows that the bulk of the debris is of local origin and has been derived from the neighbouring Archaean rocks. Since the rocks occurring around the Damodar Valley Coalfields vary in their character, the lithology of the coarse fraction is not homogeneous throughout. It is important to note, however, that occasional fragments of Vindhyan quartzite and red jaspar breccia of the Bijawar series are often present in the debris indicating a very minor admixture of rocks brought from a distant area.

A different conclusion is reached when the fine fraction of the boulder bed is examined. This fraction is extremely uniform and homogeneous with regard to its texture and composition and its constituents bear no relationship to those of the neighbouring rocks. This fraction cannot be of local origin, for in that case its character would change from one locality to another according to the nature of the bed rocks. The source of the matrix, therefore, is in all probability quite some distance upstream.

Evidence has been cited earlier to prove that the bulk of the matrix has been formed as a result of crushing of shale, slate, phyllite and greenstone fragments. It is reasonable to suggest that these fragments were brought from far off places and were crushed during glacial transport to a paste which now forms the matrix of the boulder bed.

The heavy minerals of this fraction indicate that the source area must have been one of complex petrology and probably consisted mainly of high and low grade metamorphic rocks such as gneisses and garnet, actinolite, tremolite, epidote and chlorite schists and slates. A small proportion of the material was probably derived from silicic plutonic bodies and sedimentary rocks.

<u>Direction of glacier movement</u>

In the absence of striated pavements in the area, fabric analysis provides the only reliable clue to the possible direction of the glacier movement during the deposition of the basal boulder bed. It has been shown earlier that the mean fabric direction is 147°27' (N 32°33' W - S 32°33' E). Since the regional pattern of the fabric is very uniform throughout the Damodar Valley Coalfields and taking into consideration the fabric patterns it may be suggested that the glaciers moved approximately from the north-west towards the south-east direction. It is interesting to note that Gee (1932, p. 37) suggested a similar direction of glacier movement but no quantitative data was given by him in support of his conclusions.

THE UPPER BOULDER BED

It has been shown earlier that significant differences exist between the basal and the upper boulder beds and it was suggested that probably differe agencies were responsible for their formation. The presence of 1-3% "flat iron" shaped pebbles and cobbles often with striated surfaces indicate that the debris of the upper boulder bed is of ultimate glacial origin, but its other characters explained below make it doubtful if this horizon represents undisturbed original moraines.

The values for mean roundness of quartzite pebbles and cobbles enclosed in this horizon vary from 0.510 to 0.610 and are comparable to the average value of 0.58 given by Krumbein and Sloss (loc. cit., p. 83) for glacial outwash gravels, but the values are higher as compared to those of true glacial pebbles and cobbles.

It is interesting to note that five out of six fabric diagrams of this horizon are similar to type patterns III and IV. These patterns are comparable to those given by Schlee (1957) for fluvial gravels. Only one diagram resembles type II as the long axes of pebbles and cobbles are preferentially oriented and show a tendency to an upcurrent imbrication. Moreover, there are two conspicuous transverse sub-maxima present in this type. It has been mentioned earlier that this pattern is identical with those given by Holmes (1941) and Harrison (loc. cit.) for glacial tills. It is also important to note that the upper boulder bed shows a greater scatter of the azimuthal data as compared to the basal bed. This agrees closely with the findings of Krumbein (1939, p. 701) who noted that glacial outwash deposits show poor orientation of the 'a' axes as compared to the tills because "the rapid deposition of the pebbles from the outwash waters resulted in a wide scatter of the pebble axes".

It is clear from the above that the fabric of the upper boulder bed shows the essential features of a water-sorted gravel. The remnants of the original till fabric are preserved occasionally, indicating that the debris is of ultimate glacial origin but has been turned over by water action.

The data on the mechanical composition of this horizon also supports the above conclusion. The average sand and clay contents of the fine fraction are 72.76% and 4.04% respectively. A comparison of this data with that of tills in other parts of the world shows that the sand content of this horizon is abnormally high and the clay content very much lower than is normally present in tills (Udden, 1914; Krumbein, 1933; Kay and Graham, 1943; Riecken and others, 1947; Shepps, 1953; Dreimanis and Reavely, 1953). It is suggested that the agency of running water was responsible for washing away the fine particles of the original till.

The presence of cross-bedded strata in the upper boulder bed is another evidence in support of the conclusion that the agency of running water was responsible for washing the original glacial debris. These strata are distinctly water sorted, containing only 2.85% clay on an average and enclosing rounded to well rounded pebbles, cobbles and boulders. In no case have the particles been found striated. The fabric and micropetrological studies also indicate that the cross-bedded horizons represent the completely washed and resorted portions of the upper boulder bed.

It may be concluded that the upper boulder bed represents a thoroughly washed and reworked glacial till. The debris was probably not transported to any considerable distance as the remnants of till fabric are occasionally preserved. The glacial streams emerging out of the receding glaciers were in all probability responsible for the formation of the cross-bedded horizons.

Provenance

The lithology of the coarse fraction and the micro-petrological studies of the fine fraction show that the upper boulder bed does not differ much from the basal bed in composition. Detailed studies have shown that in this horizon also the debris constituting the coarse fraction is of local origin, while that constituting the fine fraction has come from long distance upstream.

The similarity of composition between the two boulder beds could arise either as a result of an admixture of the upper till with the lower till or as a result the fact that the glaciers traversed the same area. As the two horizons are separated from each other by a considerable thickness of shales and sandstones, it is unlikely that the materials of the two horizons have mixed up. It is more likely that the lithological similarities between the two are due to the fact that both the boulder beds derived their material from a more or less common source.

Direction of sediment transport

The mean direction of preferred orientation in this horizon as indicated by the fabric diagrams is 81°20' (N 81°20' E - S 81°20' W). Taking the direction of preferred orientation as an index of the direction of sediment transport and also taking into consideration the fabric patterns, it is suggested that the ice sheet that deposited the upper boulder bed moved approximately from the west towards the east.

It is interesting to note that the mean fabric direction in the cross-bedded horizons is 89° (N 89° E - S 89° W), indicating thereby that the regional slope of the area during the early Talchir times was also from west to east.

RECONSTRUCTION OF THE EARLY TALCHIR SEDIMENTATION

The above study has brought to light some facts which appear to have an important bearing on the reconstruction of the geological conditions prevailing over the region of the Damodar Valley Coalfields during the Talchir times.

Sedimentation started in this region with the deposition of the basal boulder bed by an ice sheet which had probably moved in from the north-west. The glaciers then receded, scooping out depressions which were filled up by melt waters and later received the deposits of fine material brought by numerous glacial streams. The varved Talchir shales probably represent this phase of deposition. The presence of pebbles and cobbles in these finely laminated shales indicates that the large fragments were rafted to the site of deposition by the agency of drifting ice. As the basins were gradually filled up and became shallower, outwash sands were deposited which now constitute the sandstones. The rythm in sedimentation indicates that repeated subsidence and elevation were probably frequent.

After a lapse of considerable time, it appears that another ice-sheet moved into this region, this time from the west. It is very likely that during the recession of the first ice sheet, some changes in the level of the country on a regional scale had already taken place which changed the direction of approach of the second ice sheet from north-west to west. That such changes in level on a regional scale due to glacial melting can actually take place, is shown by the studies of Gutenberg (1933). He has shown that in the recent past tilting upward in a northerly direction has taken place in the region of the Great Lakes by about 10 cm. per 1000 km. per century. Similar changes along the Pacific and Atlantic coasts were also noted by him. This author concluded that tilting due to glacial melting took place "due to forces which tend to restore isostatic equilibrium, disturbed by the melting of ice after the ice age".

The second ice sheet deposited the upper boulder bed on top of the sand which had filled up the basins. Considering the small thickness of this boulder bed (5-15 feet) and the fact that it is very much reworked, it appears likely that the ice sheet was thin. As the climate warmed up with the approach of the Barakar times, the glaciers quickly melted away giving rise to numerous streams which almost completely reworked the upper boulder bed and imparted to it the characteristics of a glacial outwash deposit.

SUMMARY AND CONCLUSIONS

A detailed petrographic and fabric study of the Talchir boulder bed has been undertaken and an attempt has been made to establish its nature and origin in the Damodar Valley Coalfields.

The coalfields of the Damodar Valley include those of Raniganj, Jharia, Bokaro, Ramgarh and North and South Karanpura. They extend over a distance of about 168 miles, commencing from the Raniganj coalfield in the east to the Karanpura coalfields in the west. In these coalfields the Lower Gondwana rocks are well exposed but the Upper Gondwanas are poorly represented. The Talchir series is the oldest in the Gondwana sequence and is characterised by the presence of a boulder bed of Upper Carboniferous age at or near its base.

The Talchir boulder bed is often found to consist of two horizons. One, the basal boulder bed is about 50 feet thick and occurs at the base of the Talchir series; the other, designated as the upper boulder bed, is about 5-15 feet thick and occurs higher up in the series. The two boulder beds are separated from each other by varying thicknesses of shales and sandstones. The upper boulder bed often contains lenticular cross-bedded strata which are upto 5 feet thick.

The debris constituting the boulder beds is heterogeneous in character and shows a wide range of particle size. In order to facilitate the investigation, the coarse debris and the matrix were examined separately. Particles larger than 4 mm. diameter have been considered as forming the coarse fraction, while those smaller than this size comprise the fine fraction. The constituents of the coarse fraction have been studied with respect to their lithology, roundness, shape, sphericity and surface textures; the fine fraction has been investigated for its mechanical composition, micropetrology and heavy mineral content.

The coarse debris of the two boulder beds exhibits a complex and varied lithology. Pebble counts made at all the accessible exposures show that the metamorphic rocks constitute the most abundant lithologic type. The igneous rocks are of less common occurrence and the sedimentary rocks are poorly represented. The bulk of the coarse debris in both the horizons is of local origin as the pebbles and cobbles resemble the surrounding pre-Gondwana rocks. The presence of few pebbles and cobbles of Vindhyan and Bijawar ages indicates a minor admixture of rocks derived from far off places. No systematic regional variation in lithology is noticeable.

Roundness estimations using Krumbein's roundness chart, have been made on one hundred pebbles and cobbles of quartzite between ½ inch and 8 inches in diameter, at each sampling locality. It is observed that the quartzite pebbles and cobbles in the upper boulder bed and the cross-bedded horizons show a better rounding of their edges as compared to those of the basal bed. The mean roundness of the particles in the basal bed is comparable to that of tills, while in the upper boulder bed and the cross-bedded horizons it is comparable to that of the pebbles and cobbles in glacial outwash deposits.

About 5-10% of the pebbles and cobbles enclosed in the basal boulder bed are flat-iron shaped, while only 1-3% of the constituents in the upper bed are of this shape. The large particles of the cross-bedded horizons show poor development of the facetted forms. The shape data in terms of the Zingg percentages reveals that no systematic variation is present in the basal boulder bed. The upper boulder bed and the cross-bedded horizons show an increase of spherical particles and a decrease of prolate particles from west to east. There does not exist any significant variation in the sphericity values of the large particles in the different horizons. The data reveals that both the boulder beds are of ultimate glacial origin, but the upper one and the cross-bedded horizons appear to have been reworked by glacial streams.

Only a small percentage of the soled pebbles have been found to be striated. The striae are invariably sub-parallel to the long axis of the pebbles and cobbles. The grid and random patterns are conspicuously absent from the smoothed surfaces. These features show that the striation pattern on pebbles and cobbles has been produced by glacial action and not by river-ice.

Eighty samples of the fine fraction from the different localities have been analysed for their mechanical composition. This fraction in all the horizons of the boulder bed is poorly sorted and shows a polymodal size frequency distribution. Statistically the fine fraction of the basal bed is finer grained as compared to that of the upper one. This fraction is coarsest in the cross-bedded horizons. The differentiation between the various horizons on the basis of their sand, silt and clay contents, has been found valid. The textural composition of the fine fraction of the boulder beds is homogeneous. It is interesting to note that the textural composition of the basal boulder bed is comparable to that of tills, while in the upper boulder bed it resembles that of the glacial outwash deposits.

The micropetrological study of the fine fraction shows that it is texturally and compositionally immature. It has the composition of a graywacke. Soft rock fragments have substantially contributed to the formation of the matrix. The fine fraction of the cross-bedded horizons is arkosic or sub-graywacke-like and represents the reworked portions of the upper boulder bed.

The heavy mineral suits of the different horizons of the Talchir boulder bed show close similarity with one another. Garnet, zircon, epidotes, and opaques occur in all horizons. Actinolite and tremolite are fairly common to abundant in the upper boulder bed and the cross-bedded horizons, but are absent in the basal bed. Epidotes and tourmaline occur more commonly in the basal bed, while micas and chlorite predominate in the upper bed and the cross-bedded horizons. It is suggested that the provenance of the two boulder beds in the same and that the source area consisted essentially of high and low grade metamorphic rocks. A small proportion of the material was probably derived from silicic plutonic bodies and sedimentary rocks.

The measurement of the orientation of 3000 long axes of pebbles and cobbles from the various exposures shows that they are preferentially oriented.

The fabric of the basal boulder bed shows close similarity to till fabric, while that of the upper bed and the cross-bedded horizons is similar to fluvial gravel fabric. The mean fabric direction of the basal boulder bed is approximately NW-SE while that of the upper bed and the cross-bedded horizons is E-W.

On the basis of this study it is concluded that the basal boulder bed is a true tillite which has been slightly reworked by glacial waters. The ice sheet that deposited the basal boulder bed probably moved in from the north-west. The glaciers then receded leaving behind numerous lakes which served as basins of deposition for the fine material brought in by the glacial streams. The shales and sandstones separating the two boulder beds represent, in all probability, this phase of deposition. The recession of the ice sheet was probably also responsible for a slight change in the level of the region. A second sheet of ice then moved into the area from the west and deposited the upper boulder bed. This horizon was thoroughly reworked by glacial streams and the characteristics of a glacial outwash deposit were impressed upon it. The cross-bedded horizons represent the completely washed and reworked portions of the upper boulder bed.

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EXPLANATION OF PLATES

PLATE 1

Fig. 1. A typical view of an outcrop of the basal boulder bed showing an unsorted and unstratified angular to subrounded debris lying in an abundant fine-grained matrix.

Dudhi river cutting about 1½ miles up-stream from road bridge, West Bokaro coalfield.

Fig. 2. A close-up of an outcrop of the basal boulder bed showing very poor sorting. Pebbles, cobbles and boulders of metamorphic rocks are embedded in an abundant fine-grained compact matrix.

Stream cutting about ½ mile east of Rais station, North Karanpura coalfield.

PLATE 2

Fig. 1. A view of the upper boulder bed showing rounded to sub-angular pebbles and cobbles embedded in a dark, loosely compacted matrix. The boulder bed shows crude stratification.

Railway cutting about 1 mile east of Chandrapura station, Jharia coalfield.

Fig. 2. A general view of the upper boulder bed showing a crude stratification of the matrix. The long axes of the majority of pebbles and cobbles are preferentially oriented.

Tributary of the Dudhi river about 1½ miles west of the road bridge, West Bokaro coalfield.

PLATE 3

Facetted flat-iron shaped pebbles enclosed in the basal boulder bed showing pentagonal, quadrangular and triangular outlines. (About half the natural size)

MICRO-PHOTOGRAPHS

BASAL BOULDER BED

PLATE 4

Fig. 1. Fine fraction showing very poor sorting and an abundance of fine-grained chloritic matrix. Clear quartz and turbid felspar grains which are sharply angular to sub-angular make up the bulk of the framework. A wide and continuous range of particle size is note worthy.

Near Ray station along railway cutting, North Karanpura coalfield. (x 40)

Fig. 2. Fine fraction showing very poor sorting and an abundance of paste-like chloritic matrix. Quartz grains are sharply angular while felspars are sub-angular. A fragment of phyllite at the top left corner is rounded while a quartzite fragment in the centre is angular. A wide and continuous range of particle size is characteristic.

South of Chapri, South Karanpura coalfield. (x 40)

Fig. 3. Fine fraction showing poorly sorted, angular debris with a wide and continuous range of particle size. Quartz grains with sharply angular outlines are very common. A fragment of shale at lower right-hand side is sub-rounded. Paste-like matrix is abundant.

Dudhi river section about 1½ miles upstream from road bridge, West Bokaro coalfield. (x 40)

Fig. 4. Fine fraction showing very poor sorting and an abundance of chloritic matrix. A large quartz grain in the lower middle portion is sub-rounded and "snubbed" at the lower margin; the small quartz grains are sharply angular. Felspars are angular to sub-rounded while a greenstone fragment at the lower left-hand corner is sub-rounded. Marginal replacement of quartz grains by the matrix is seen in the upper right-hand part.

Stream cutting, West of Purnu, Ramgarh coalfield. (x 40)

PLATE 5

Fig. 1. Fine frastion showing a very poorly sorted debris with a wide and continuous range of particles size. Sharply angular to sub-rounded fragments lie in an abundant chloritic matrix.

Jamunia river section, about 3 furlongs from the sharp bend in the river, Jharia coalfield. (x 40)

Fig. 2. Fine frastion showing abundant chloritic matrix in which are scattered sharply angular fragments of quartz. Altered felspar grains in the left-hand centre are rounded to sub-rounded.

North of Tetulia, Raniganj coalfield. (x 40)

Fig. 3. A large slaty fragment with regularly arranged opaque inclusions (? Ilmenite) shows a distinct and unobliterated outline. Clear quartz felspar grains in the lower part show conspicuous marginal replacement by the fine chloritic matrix.

Jamunia river section, about 3 furlongs from the sharp bend in the river, Jharia coalfield. (x 120)

Fig. 4. A large schistose fragment showing effects of flow in response to pressure. The fragment is spindle shaped and has bent round the quartz grain in the lower part while flowage is clearly seen in the top middle and lower left-hand parts where it has been squeezed between quartz grains.

Stream cutting about 1 mile, North of Dharvaiya, Ramgarh coalfield. (x 120)

PLATE 6

Fig. 1. A large fragment of shale along the right-hand edge and two smaller ones to the left of it appear to have flowed in-between the more resistant quartz grains. The smaller grains are very much sheared and, at places, merge into the matrix.

About a mile north-west of Dhavaiya, Ramgarh coalfield. (x 120)

Fig. 2. An elongated and sheared fragment of shale bent around an angular quartz grain and showing considerable distortion due to flowage. A large orthoclase grain at the top left-hand side is completely kaolinised and merges into the matrix. An angular quartz grain in the top central part contains numerous mineral inclusions.

About a mile north-west of Dhavaiya, Ramgarh coalfield. (x 120)

Fig. 3. A large fragment of chloritis shale merging into the matrix. The boundary between the two is very indistinct. Texturally and compositionally the matrix is indistiguishable from the rock fragment.

Stream cutting west of Punu, Ramgarh coalfield. (x 40)

Fig. 4. A chloritic rock fragment occupying the central and upper parts is hardly distinguishable from the matrix with which it shows remarkable textural and compositional similarity. This is a clear evidence of the matrix having been derived mainly from the crushing of rock fragments.

About a mile west of Ray station along railway track, North Karanpura coalfield. (x 120)

PLATE 7

Fig. 1. A large bunch of muscovite flakes in a poorly sorted angular debris consisting essentially of quartz. The flakes are bent and show frayed ends. The matrix material has penetrated along cleavage planes and has even physically disrupted a few flakes along these planes as seen at lower left-hand corner. This indicates that the flakes are of detrital origin. A quartz grain in the upper central part of the bunch with which they are intergrown suggests a pematitic source for this fragment.

Benjor section near railway track, Jharia coalfield. (x 40)

Fig. 2. A large angular quartz grain showing corrosion of its boundary by the chloritic matrix. The boundary of the grain is fuzzy and shows many inlets of the matrix. Numerous acicular inclusions arranged randomly and clusters of dusty inclusions are noteworthy.

East of Ray station in the stream cutting near railway track, North Karanpura coalfield. (x 120)

Fig. 3. A large angular fragment of quartz showing replacement by matrix material. The replaced boundary is indistinct. Numerous smaller grains are similarly replaced, indicating a strong tendency for reorganisation of the matrix.

West of Poonu, Ramgarh coalfield. (x 120)

Fig. 4. A chloritised basalt fragment showing partial replacement by the matrix, while a part is still rounded and unaffected.

Near Ray station, North Karanpura coalfield. (x 40)

UPPER BOULDER BED

PLATE 8

Fig. 1. A general view of the fine fraction showing a very poorly sorted consisting of abundant rock fragments and angular quartz grains set in a chloritic, paste-like matrix. Rock fragments are rounded but the two chloritic fragments, one on the left-hand and the other on the right-hand centre show indistinct boundary outlines. These may constitute a possible source of the abundant matrix material which is of similar composition.

About half mile east of Telesdih, Misroul area, North Karanpura coalfield. (x 40)

Fig. 2. A general view of the fine fraction showing very poor sorting and an abundance of fine matrix. Quartz grains are angular and show a continuous range of size while felspars are sub-angular to rounded.

Tributary of the Dudhi river about 1½ miles west of the road bridge, West Bokaro coalfield. (x 40)

Fig. 3. A general view of the fine fraction showing a poorly sorted angular debris set in an abundant chloritic matrix. A fragment of graphic granite showing intergrowth between orthoclase (kaolinised and quartz is seen at the right-hand top corner.

About half mile east of Chandrapura railway station near the bifurcation of the railway track, Jharia coalfield. (x 40)

Fig. 4. A general view of the fine fraction showing a very poorly sorted debris consisting of angular quartz, rounded felspar and large rounded rock fragments. In the bottom right-hand corner a large rock fragment shows an inlet of the matrix indicating replacement of the former by the chloritic matrix.

About two furlongs west of Pooru on the road to Palu, Ramgarh coalfield. (x 40)

PLATE 9

Fig. 1. A magnified view of the right-hand bottom corner of Plate 8, Fig. 4 showing the inlet of the groundmass into the coarse grained rock fragment (granite). The inlet occurs in a large orthoclase grain and shows the irregular nature of replacement.

About two furlongs west of Pooru on the road to Palu, Ramgarh coalfield. (x 120)

Fig. 2. A cluster of fresh biotite flakes showing perfect cleavage and curved outlines. The flakes are distinct in the central part of the cluster but hazy and indistinct in the peripheral part where they are indistinguishable from the chloritic matrix. This is probably a product of re-crystallisation of the matrix.

About half a mile east of Chandrapura railway station near bifurcation of the railway track, Jharia coalfield. (x 120)

Fig. 3. A large quartz grain appreciably eaten away by the matrix. The original boundary outline is feebly visible towards the left.

Tributary of the Dudhi river about 1½ miles west of the road bridge, West Bokaro coalfield. (x 120)

Fig. 4. A large rounded grain of quartz showing patches and rows of dusty inclusions. The rock is very poorly sorted and contains abundant chloritic matrix.

About half mile west of Pooru, Ramgarh coalfield. (x 40)

CROSS-BEDDED HORIZONS

PLATE 10

Fig. 1. A general view of the fine fraction of the cross-bedded horizons showing intact framework. The debris is rather poorly sorted and the fragments are rounded to angular. Compositionally it is a lithic sub-graywacke.

About ½ mile east of Teleadih, North Karanpura coalfield. (x 40)

Fig. 2. A general view of the fine fraction of the cross-bedded horizon showing a moderately sorted, rounded to sub-rounded debris. Detrital matrix is less than 5%. Compositionally it is an arkose.

Tributary of the Dadhi river about 1½ miles west of the road bridge, West Bokaro coalfield. (x 40)

Fig. 3. A general view of the fine fraction of the transition zone between the cross-bedded units and the enclosing boulder bed. The debris is poorly sorted, sharply angular to rounded with abundant matrix (about 25%). Compositionally it is a graywacke.

Two furlongs south-east of Chapri, East Bokaro coalfield. (x 40)

Fig. 4. A magnified view of the matrix of the transition zone between the cross-bedded units and the enclosing boulder bed showing the sharply angular nature of the quartz and felspar grains. A rounded grain of garnet in the top left-hand side and sub-rounded to angular grains of epidote in the bottom right-hand corner are conspicuous.

¼ mile south of Bookra, North Karanpura coalfield. (x 120)

Plate. I.

Fig. 1.

Fig. 2.

Plate. II.

Fig. 1.

Fig. 2.

Plate. III.

Plate. IV.

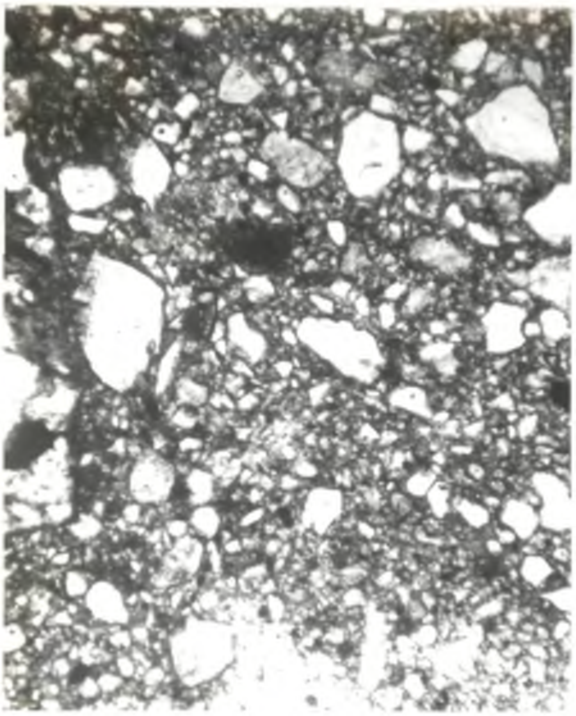
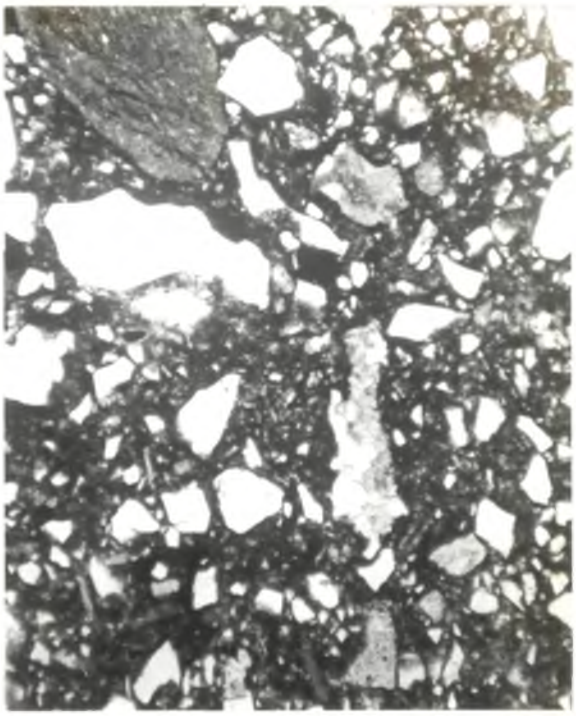


Fig. 1. (X 40)



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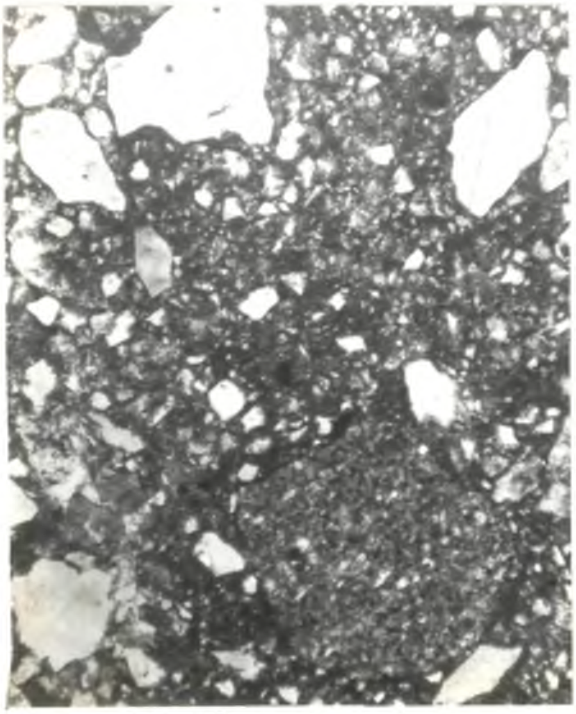


Fig. 3. (X 40)

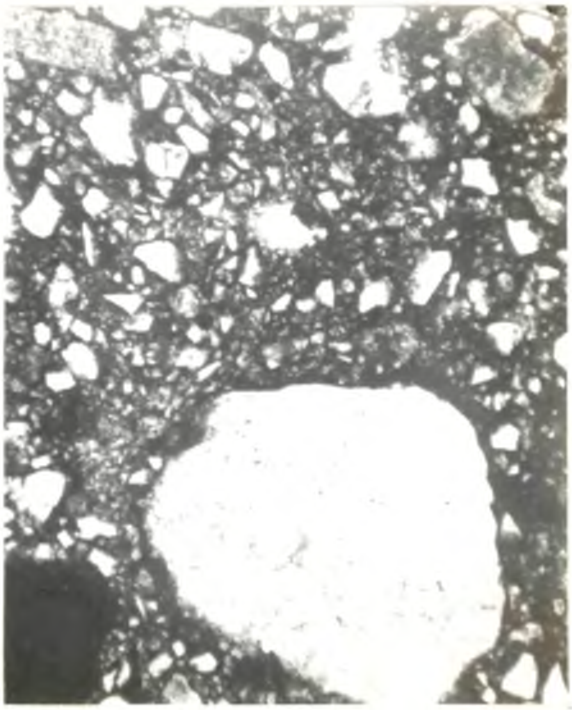
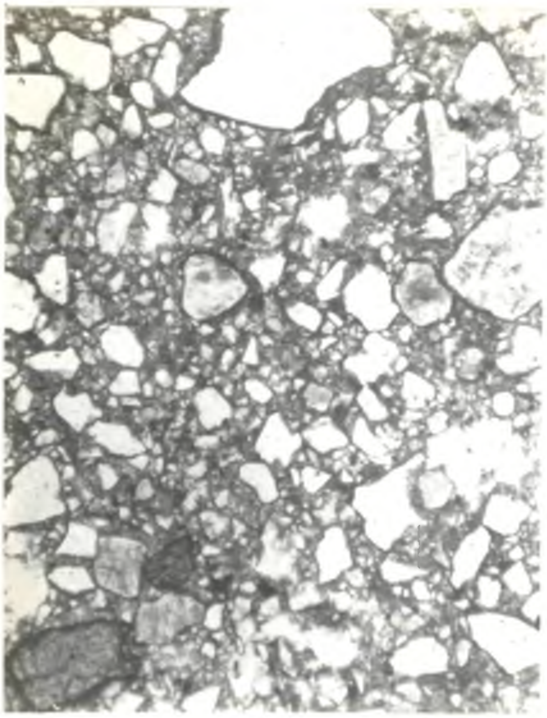


Fig. 4. (X 40).

Plate. V.



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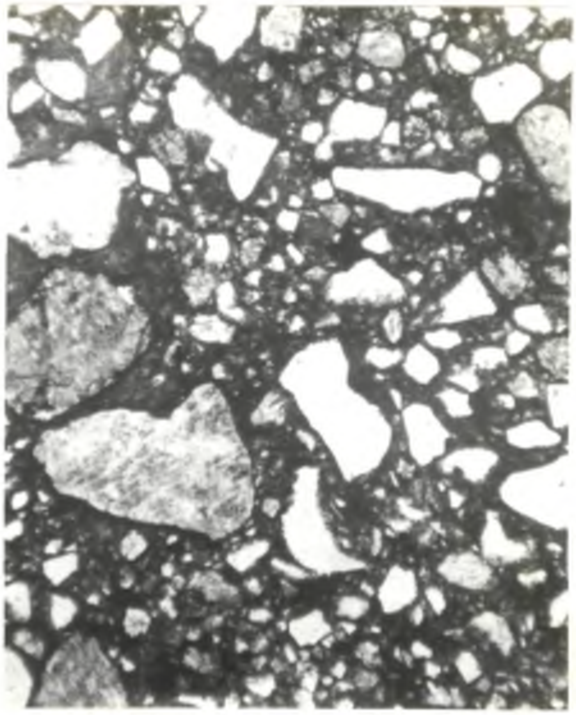


Fig. 2. (x 40).

Fig. 3. (x120)

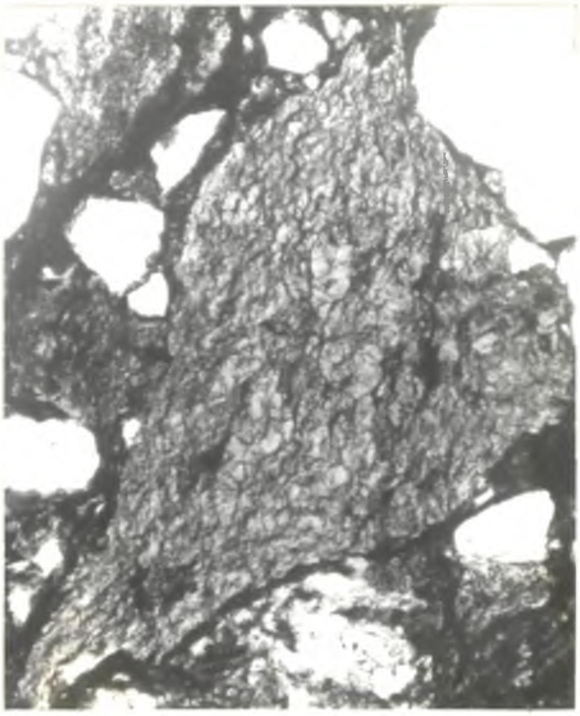
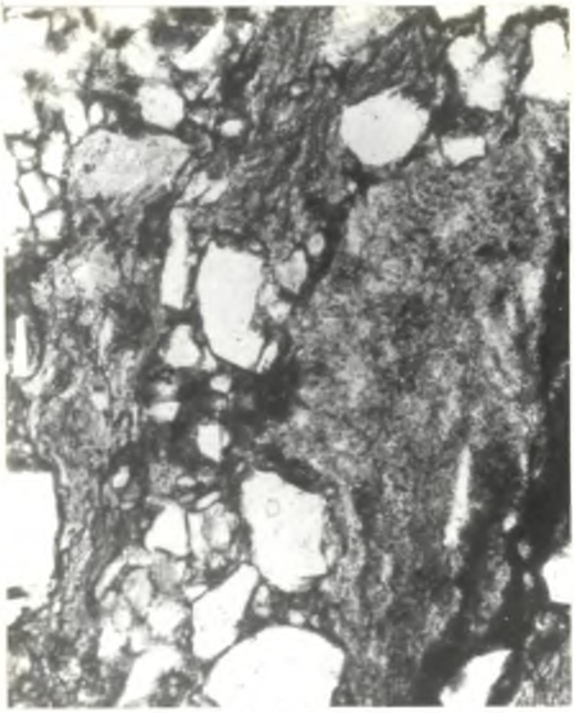


Fig. 4. (x120).

Plate. VI.



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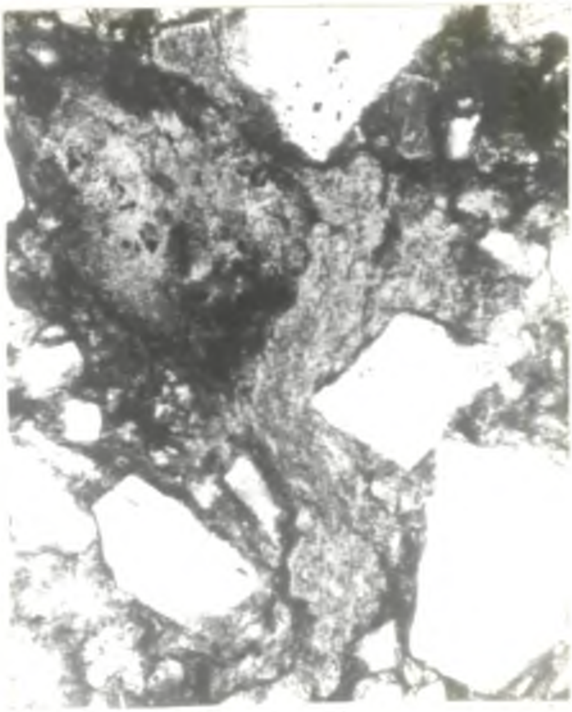

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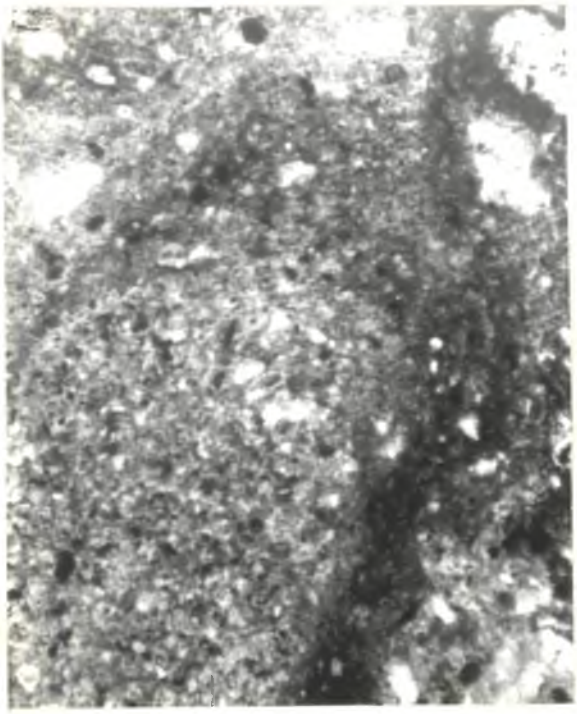

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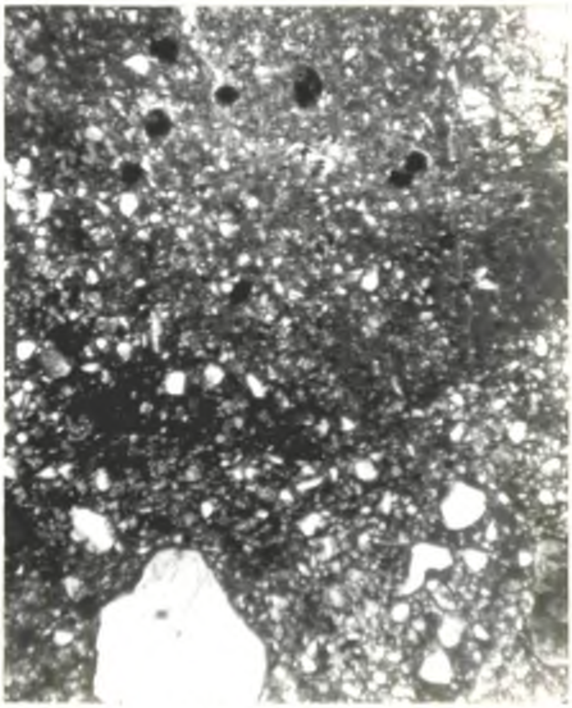


Fig. 4. (x120).

Plate. VIII.

Fig. 1. (x 40)

Fig. 2. (x 120).

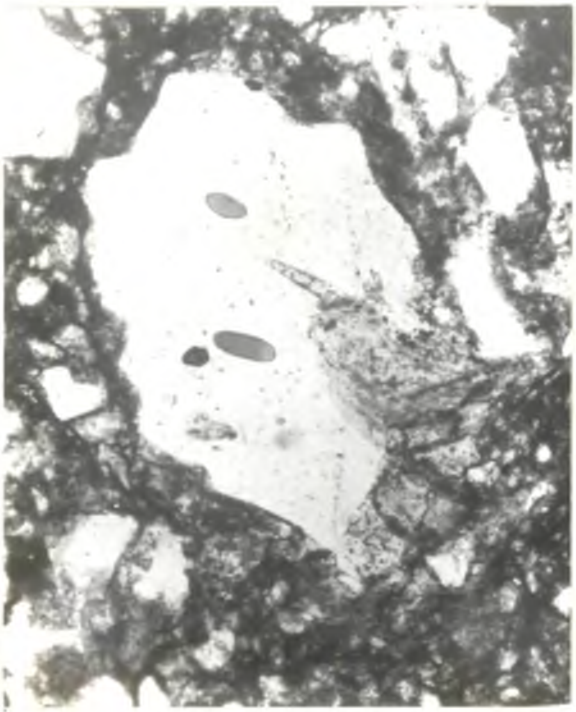


Fig. 3. (x 120).

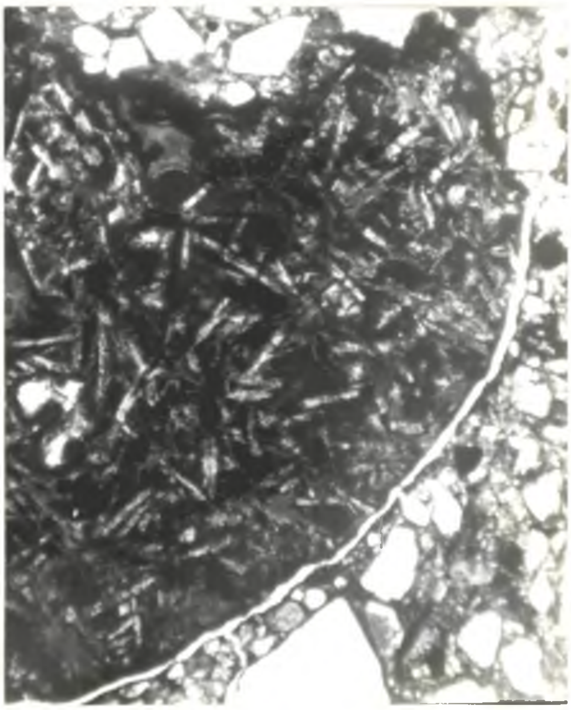


Fig. 4. (x 40).

Plate. VIII.

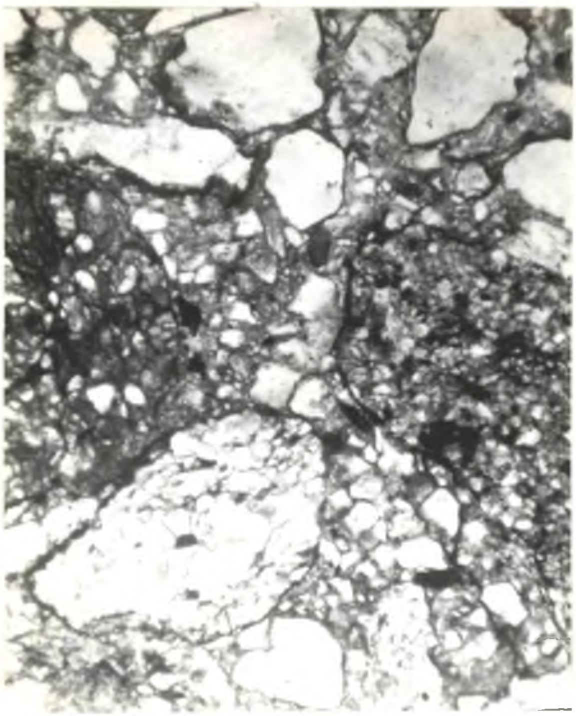
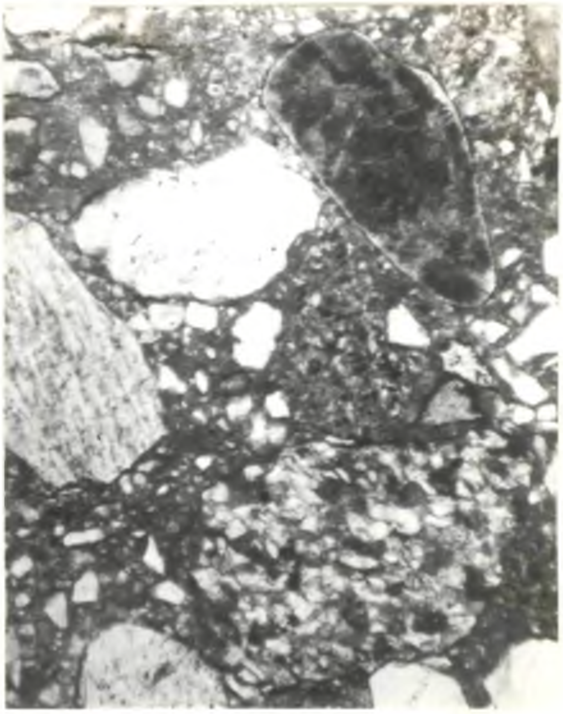


Fig. 1. (×40).



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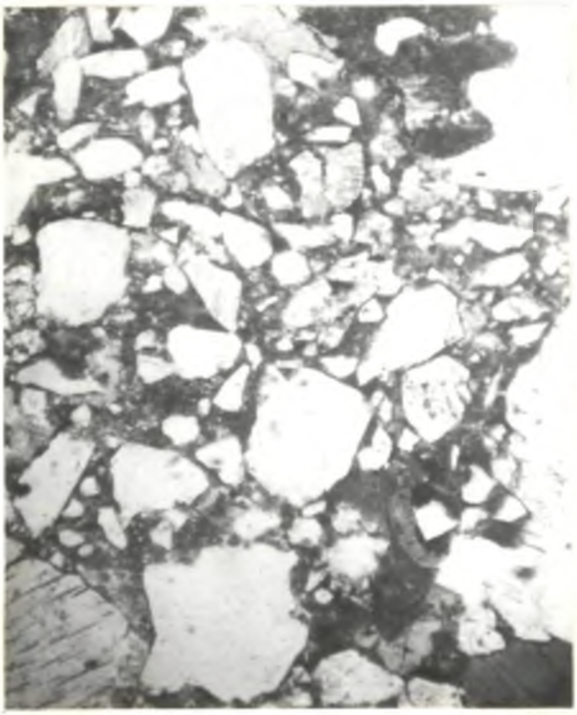

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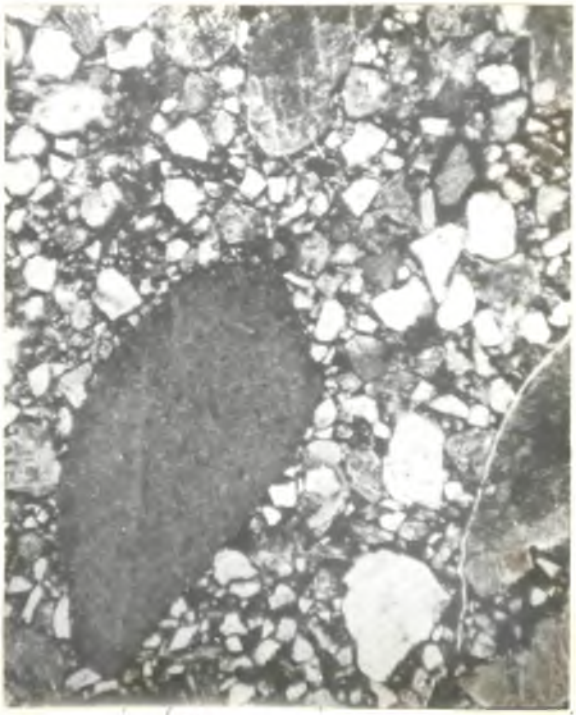


Fig. 4. (×40).

Plate. IX.

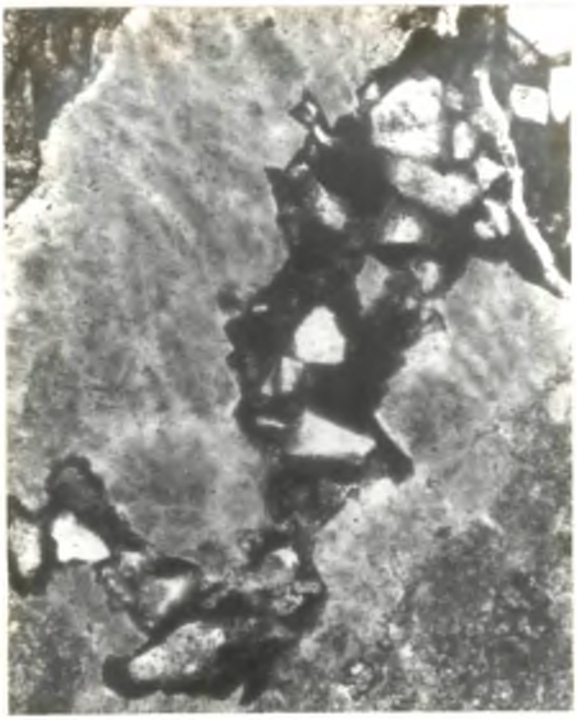


Fig. 1. (x120).

Fig. 2. (x120).

Fig. 3. (x120)

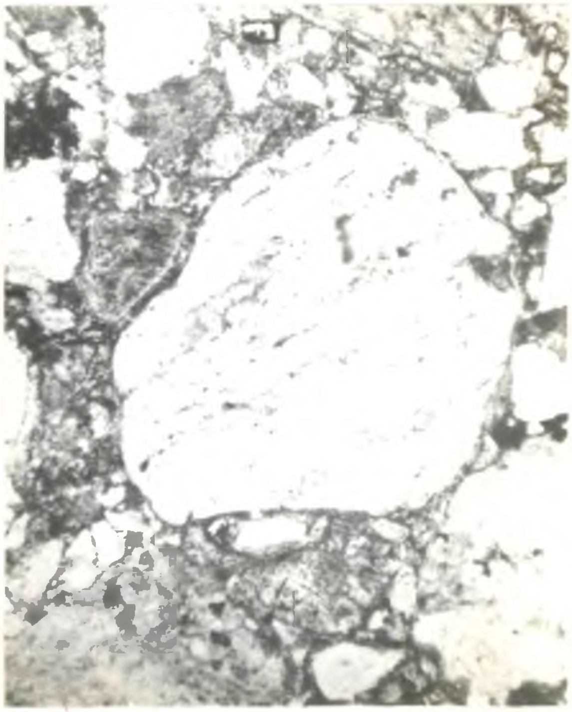


Fig. 4. (x40).

Plate. X.

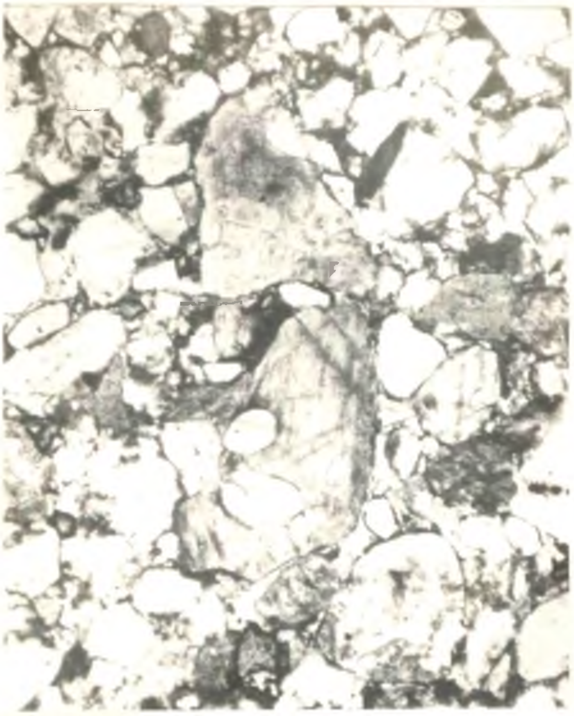
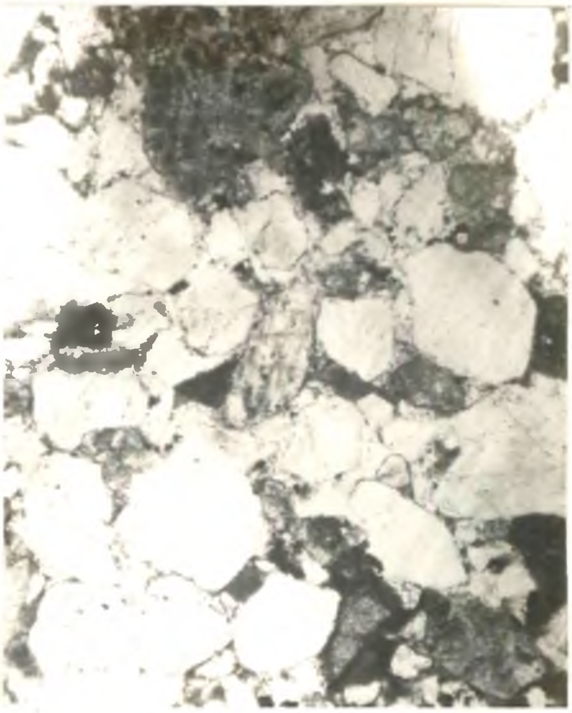


Fig. 1. (×40).



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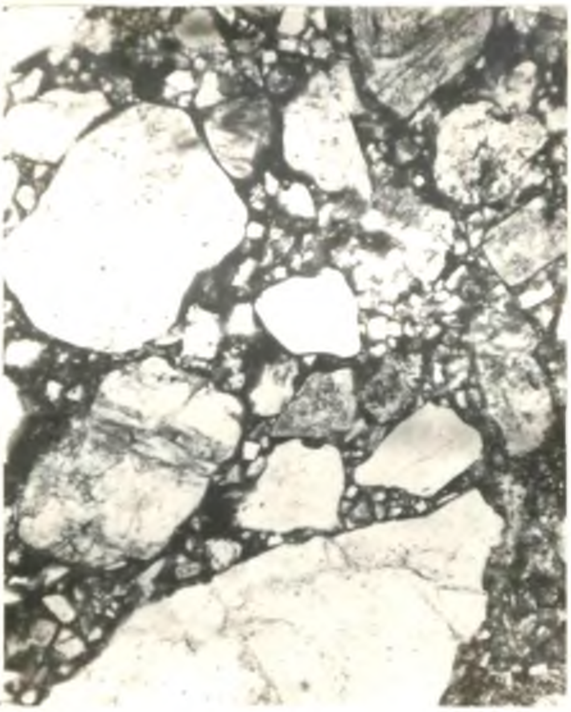

Fig. 3. (×40).

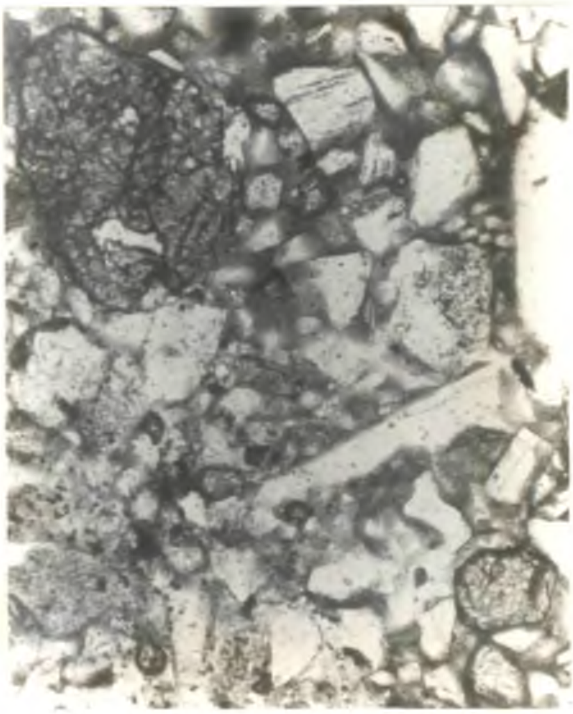

Fig. 4. (×120).

BREAK